NOAA Special Report

New England Offshore Mining Environmental Study (Project NOMES)

Final Report

John W. Padan, Editor

April 1977

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
Environmental Research Laboratories

NOAA Special Report

New England Offshore Mining Environmental Study (Project NOMES)

Final Report

John W. Padan

Pacific Marine Environmental Laboratory
Seattle, Washington

April 1977

U.S. DEPARTMENT OF COMMERCE
Juanita M. Kreps, Secretary

National Oceanic and Atmospheric Administration
Robert M. White, Administrator

Environmental Research Laboratories
Wilmot Hess, Director

Boulder, Colorado

NOTICE

The Environmental Research Laboratories do not approve, recommend, or endorse any proprietary product or proprietary material mentioned in this publication. No reference shall be made to the Environmental Research Laboratories or to this publication furnished by the Environmental Research Laboratories in any advertising or sales promotion which would indicate or imply that the Environmental Research Laboratories approve, recommend, or endorse any proprietary product or proprietary material mentioned herein, or which has as its purpose an intent to cause directly or indirectly the advertised product to be used or purchased because of this Environmental Research Laboratories publication.

This report is dedicated to the men and women of the Marine Minerals Technology Center, a NOAA laboratory closed in 1973. The New England Offshore Mining Environmental Study (NOMES) was initiated as a result of the Center's interest in the environmental effects of marine mining. In a way, this report is a legacy of MMTC.

CONTENTS

Page

PREFACE

Principal investigator reports to NOAA are listed in Sections 6 and 7. In some cases the reports have been published and so only summaries are included here. Any errors in the integration and synthesis of the researchers' findings rest solely with the author of this report. Following are the principal investigators, with reference to sections of this report in parentheses:

Biological Oceanography:

Dr. Larry G. Harris and Dr. Arthur C. Mathieson, U. of New Hampshire (Benthos)
Dr. Hugh F. Mulligan, U. of New Hampshire (Phytoplankton)
Dr. Richard K. Peddicord, U. of California (Turbidity experiments)

Geological Oceanography:

Dr. Clarence L. Grant, U. of New Hampshire
Mr. Loren W. Setlow, Commonwealth of Massachusetts

Chemical Oceanography:

Dr. Arthur I. Ippen and Dr. Erik L. Mollo-Christensen, Massachusetts Institute of Technology

Physical Oceanography:

Dr. Arthur I. Ippen and Dr. Erik L. Mollo-Christensen, Massachusetts Institute of Technology

Dr. Hugh F. Mulligan, University of New Hampshire

SUMMARY

The New England Offshore Mining Environmental Study (Project NOMES) was begun in 1972 in order to resolve the marine environmental impact uncertainties that had inspired at many levels of government legal and de facto moratoriums on marine mining. It was a joint study sponsored by the Commonwealth of Massachusetts and the National Oceanic and Atmospheric Administration. Plans had called for a 1-year study of baseline conditions at a sand and gravel deposit centered in Massachusetts Bay at 40°21'41" N., 70°47'10" W., followed by a period of well-monitored commercial-scale mining. Two years of post-experiment monitoring were planned to document mining-induced changes in the seafloor and water column as well as their subsequent alteration by natural processes.

The project was terminated in July 1973 as a result of the failure of the Commonwealth to arrange for a suitable site for the disposal of the three-quarters of a million cubic meters of sand and gravel to be mined during the planned spring 1974 test. Nevertheless, all principal investigators were funded through a project wrap-up phase, and two were funded long enough to permit them to study baseline conditions in two important aspects of marine life (i.e., benthos, phytoplankton) for a full year.

The purpose of this report is to consolidate and present the findings in such a manner that the NOMES experience can be considered an informational and procedural point of departure for studies preceding the next continental sand and gravel venture, whether it be an experiment or a commercial mining operation. Studies are reported in four areas of oceanography: biological (benthos, phytoplankton, turbidity experiments), geological (bathymetry, stratigraphy, core samples), chemical (nutrients, suspended solids), and physical (temperature and salinity, currents and dispersion, and light penetration).

Over 650 species of benthic invertebrates were sampled by scuba diving at a number of stations arranged in a grid pattern around the test site. The most important result of this part of the project was the documentation of the natural variability in the system. The existence of month-to-month variation at each station was the most consistent finding. From month to month there was up to 100% variation in the number of species at a station. In fact, the species numerically dominant one month frequently were absent from collections in the next month. The species tended to change with substrate type. This is a heterogeneous environment and only a minority of the species appeared to be specialists for substrate type. Indicator species, if it is possible to use them in the future, will most likely have to be selected for each station and not from general substrate types. In a future study of offshore sand and gravel mining, benthic community studies should utilize permanent stations, as was done in NOMES, but the sampling scheme should be altered. A limited number (two to four) of stations should be sampled intensively on a quarterly schedule. Fifteen to twenty replicate samples should be taken at each station every three months and analyzed separately so that aggregated distributions can be identified. This may provide a more realistic picture of community organization and dynamics than monthly sampling with fewer replicates would.

Phytoplankton also were sampled on a grid around the test site and coordinated with measurements of salinity, temperature, and light penetration as well as samples taken at the same time for water chemistry determinations. Analyses of species composition and distribution and abundance of phytoplankton populations revealed considerably more variability from station-to-station analyses than from diurnal analyses at a single station. These station-to-station analyses allowed an interpretation of phytoplankton developmental trends. For example, inshore to offshore trends in the seasonal development of phytoplankton populations were documented. The proposed test site appeared to be located at the center of a large gyre. It was observed that the 16-station (36 square mile) grid could be separated into two reasonably discrete regions, by a line drawn through the center of the grid along a northeast to southwest axis, separating coastal phytoplankton populations from oceanic populations. (Largest phytoplankton populations and highest primary productivity levels occurred within the southwesterly portion of the grid.) Most of these trends would have been missed had the sampling proceeded at a single station over a 12-hr tidal cycle or along single transects drawn perpendicular to the shore. The grid design provided the best indication of plankton dynamics in this portion of Massachusetts Bay and is highly recommended for a future study of offshore sand and gravel mining.

Turbidity experiments were conducted at the unique aquarium complex at the University of California's Bodega Marine Laboratory in Bodega Bay, California. It was hoped that studies of organisms analagous to those in Massachusetts Bay would reveal the reasonableness of extrapolating findings of such studies. Experiments with varying levels of suspended sediment were conducted on both marine and estuarine organisms. Initial tests were conducted with suspended particles of kaolin, a "pure" clay; sensitive species were then exposed to bentonite, an "impure" clay more representative of San Francisco Bay sediments. Most exposure tests were conducted for 10 days. Mortality was analyzed every 8 hr and LC50, 20, 10 estimates made. From that information, time-concentration curves were developed. One of the most significant findings was that tolerance to suspended bentonite seemed to be correlated with normal habitat of the organisms. No species living primarily in close association with mud bottoms was found to be sensitive. All sensitive test species were either invertebrates occurring predominantly on sandy bottoms or in fouling communities, or fish not intimately associated with the bottom.

Bathymetric measurements revealed an irregular bottom topography with NNW.-trending ridges interspersed with depressions. The shape of the seafloor is characteristic of an area that has experienced glacial activity.

Subbottom profiling supplemented by core drilling revealed the existence of a deposit containing over 5 million cubic meters of sand and gravel. This deposit appears to be a gradational feature resting on a marine clay that is underlain by glacial till.

Core samples were found to consist of 25 to 30% plagioclase and orthoclase, 20 to 30% quartz, 15 to 20% hornblende, 5 to 10% biotite and muscovite, minor amounts of a variety of other minerals, and about 5% shell fragments and *Foraminifera* tests. Analyses for sulfides, phosphorous, mercury, trace metals, and other potential pollutants showed that the planned mining test itself was not likely to cause an environmental impact (i.e., the deposit was declared "clean").

As noted above, sampling for chemical oceanographic determinations was performed at the same time and in the same grid as phytoplankton sampling. The higher concentrations of $N\text{-}NO_3$, $P\text{-}PO_4$, and suspended sediments were found closer to shore. Normal spring blooms can most clearly be seen in the nitrate plots since nitrogen seemed to be the limiting growth factor. Nitrogen-nitrate reached a peak concentration in winter and then dropped to undetectable levels coincident with the development of the phytoplankton. This observation leads to the suggestion that nitrogen is a limiting nutrient. (However, since no analyses were attempted for $N\text{-}NH_4$, one cannot conclude that nitrogen was a limiting element.) Phosphate-phosphorus appeared to be present in excess even during the bloom. The nutrient concentrations that normally occur are increased by sewage effluent discharges to Boston Harbor.

The main reason for the study of the physical oceanographic characteristics of the area was the need to relate water mass movements to phytoplankton and water chemistry sampling.

The chief topographic feature affecting the physical oceanographic character of the test area is Stellwagen Bank, a submarine ridge that rises to within 20 m of the ocean surface on the east side of Massachusetts Bay between Cape Ann to the north and Cape Cod to the south. This ridge blocks the free exchange of water at depth between the bay and the Gulf of Maine.

Historically, the whole water column is thoroughly mixed in the winter, but a weak vertical temperature gradient starts to appear in late March as the surface begins to warm. In 1973, maximum surface temperature was reached in August at which time the thermocline strengthened between 5 and 15 m. By early November the water column had returned to an isothermal state.

In 1973 the salinity at the surface ranged between 30 and 33°/₀₀, with the minimum in May and a maximum in March. In general, the surface isohalines trend north and south with salinity increasing offshore. The mean bottom salinity ranges from 31.6 to 32.5°/₀₀. The minimum salinity is observed at all depths in May as a result of the spring runoff. Temperature/salinity data show that the warming cycle which commences in March continues to August at the surface and to October at the bottom, when it begins to chill back to the February condition. Salinity is at maximum during the coldest period, freshens throughout the water column to a minimum in May in response to runoff and gradually (through mixing and advection) returns to the winter maximum.

A drogue and dye survey in 1972 showed that non-tidal currents in the area of the test site were to the south in the initial stages of both flood and ebb tides. For the flood tide the 1.5-m (depth) drogues traveled in a southeast direction with an average velocity of 27 m/s while the 9-m drogues traveled in a southwest direction with an average velocity of 11 m/s. For the ebb tide both sets of drogues started out at an almost due south heading until the 1.5-m drogues shifted to a westerly and then a northwesterly heading. At the same time the 9-m drogues shifted to an easterly and then a northeasterly heading. The dominant southward component of the movement was an unexpected result of this survey at the time. The average dispersal rate was 10 m^2/s for the ebb tide and 3.4 m^2/s for the flood tide.

A test particle dispersion study was conducted in 1973, 1 year prior to the planned experimental dredging, in order to develop a technique to predict where a dredge discharge silt plume might travel in response to prevailing currents and winds. In brief, 2700 kg of small ($0.5 < d < 50$ μm) particles were released to the water surface at the mine site, and their movement was tracked for 10 days. Also, oceanographic data were collected by drogues and moored current meters, and a dispersion model was formulated. The observed dispersion of the plume was toward Boston Harbor, eastward toward Stellwagen Bank, and then southward along the coast into Cape Cod Bay where a counter-clockwise gyre was suggested. Although the particles may not have behaved exactly as a real dredge plume, they were a more reasonable indicator of dredge plume dispersal and behavior than dissolved traces, which do not exhibit the sedimentary characteristics of particles. The dispersion of the particles was governed by the tidal cycle at time of introduction, the seasonal structure of the water column, and the effect of a storm that mixed the upper waters to a depth of 30 m. The particles were found to concentrate at or above the base of the thermocline. The barrier or retardant to settling may have caused greater lateral dispersion in the upper water layer than might have occurred in winter. The dispersal rate appeared to be 30 m^2/s.

Light penetration measurements showed that maximum penetration occurred during winter, and minimum in late March because of spring runoff and phytoplankton development.

RECOMMENDATIONS

Without adequate planning, the natural resource supply problems one can foresee are going to become more and more common. With respect to the subject of this report, it seems sensible for State and Federal planners to consider the mining of continental shelf sand and gravel deposits where industrial interest exists. The environmental question should be expanded to include the entire spectrum of issues facing coastal zone managers. Candidate test sites should be selected from areas where favorable marine geology and industrial interest coincide with interest on the part of coastal zone planners. Whether the resource lies in State waters or on the Outer Continental Shelf, local citizens should be included early in the planning process because the resource is going to be delivered to the coastal zone for processing and marketing. Some sort of impact is inevitable.

On the technical front a better method has to be developed to describe and compare benthic communities. If benthic effects constitute the heart of this mining uncertainty, one must learn how to distinguish changes due to mining from those due to the extreme variability inherent in the coastal marine environment. Until this can be accomplished, there seems little point in embarking on another multi-year study.

In addition, laboratory studies of the effects of turbidity on marine organisms should be continued. This work should be broadened to include nonphysiological responses, such as organisms' avoidance of a turbidity plume. Although not as important in the total scheme of things as the benthic community research, it may be extremely relevant to local commercial fishermen.

Once a site has been agreed upon, a 2-year period should be devoted to premining studies--at least the first time. The first year should be devoted to the development of sound sampling and test procedures for coordinated use the second year. The main focus of the baseline studies should be the long-term effects of a change in substrate characteristics caused by the blanket of fines. The studies in France (Cressard, 1975), although modest in scope, would probably provide some results applicable to the United States and should be evaluated as soon as possible.

While not essential, it would be economical in the long term if laboratory turbidity studies were conducted both on-site and elsewhere, in order to learn if organism reactions are analagous and therefore usable for predicting consequences of mining in new areas.

The mining test should be at a commercial scale and should continue for at least 1 year. Too brief a period of mining will not convince skeptics of the reasonableness of the extrapolation of findings to long-term mining through other seasons.

Although the period of mining must be well-monitored, the post-mining environment can be examined less frequently but should continue for at least 2 years.

In brief, the next continental shelf sand and gravel mining test probably should involve a commercial operation. It should be preceded by 2 to 3 years of involvement on the part of local planners and concerned citizens, 2 years of which should include scientific fieldwork. Prior to the initiation of a quest for a candidate site, a technique should be developed to more effectively study benthic communities. Toward that end the French experiment (Cressard, 1975) should be evaluated immediately.

NEW ENGLAND OFFSHORE MINING ENVIRONMENTAL STUDY

(PROJECT NOMES)

John W. Padan

Abstract. Findings of a study, established to investigate the potential hazard to the environment of offshore sand and gravel mining but prematurely terminated, are presented as a baseline for further studies. The original plan is fully outlined. It includes determination of the kinds of environmental impacts likely to result from hydraulic dredging; a research strategy to measure such impacts; and specific investigations to implement that strategy in four oceanographic aspects--biological (benthos, phytoplankton, turbidity experiments), geological (bathymetry, stratigraphy, core samples), chemical (nutrients, suspended solids), and physical (temperature and salinity, currents and dispersion, and light penetration). Detailed findings of completed studies are presented. A summary and recommendations appear as a foreword. Appendices provide a description of the complete process of offshore mining, from exploration to transportation to market; lists of Project NOMES Advisory Committees; and baseline data regarding benthic communities.

1. INTRODUCTION

Not until the early 1970's did it become clear that the twin pressures of expanding world population and an omnipresent desire for an ever higher standard of living would really result in a natural resources supply problem. With respect to minerals, man has always been able to discover and utilize larger and larger ore bodies of lower and lower quality. The recent substantial rise in the cost of energy, coupled with environmental constraints at home and political uncertainty in certain foreign sources of supply, are causing a reassessment of the traditional philosophy, "There is no shortage of mineral resources in sight."

The solution to the supply problem requires several parallel investigations. One of them involves broadening the mineral resource base by utilizing new types of mineral deposit exploration targets. The ocean floor offers one such target.

Although industry can be counted on to discover and utilize marine minerals, the Federal Government has a role to insure that new technology does not harm the marine environment in a significant way. Efforts to determine some of the effects are the subject of this report.

Specifically, continental shelf sand-and-gravel has been identified as one mineral commodity of substantial potential. The New England Offshore Mining Environmental Study (NOMES) was established in order to understand that aspect of marine sand and gravel mining which poses the most immediate, if not the greatest potential hazard to the environment--the hydraulic dredging operation itself.

Through NOMES we expected to understand the nature of the dredging impact (how it occurs, factors determining its extent and influence), to develop techniques to predict the probable localized effect of proposed dredging operations, and to develop environmental guidelines for government use in establishing operating regulations.

Plans called for a 1-year period of field studies in the vicinity of a potentially commercial deposit of sand and gravel in Massachusetts Bay (fig. 1), 16 km east of the Boston Harbor entrance, 2.8 km west of the Boston Lightship, and 8.9 km northeast of the northern end of Nantasket Beach, closest point to the mainland. This was to have been followed by a short period of heavily monitored commercial-scale mining, as an experimental field test to verify environmental impact predictions with data from an irregularly oblong area approximately 1.5 km long and 0.6 km wide trending N. 20° W. and centered at 42°20'41" N., 70°47'10" W. Two years of post-experiment monitoring were planned, to discover how mining-induced changes in the seafloor and water column are altered by natural processes.

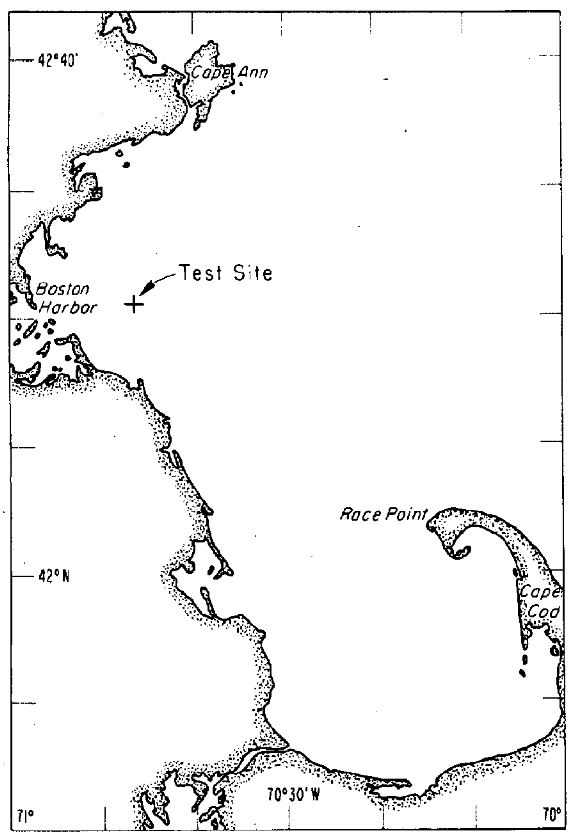


Figure 1. Test site in Massachusetts Bay.

Project NOMES was canceled in July 1973 as a result of the failure of the Commonwealth of Massachusetts (NOAA's partner in this intrastate-waters project) to arrange for the satisfactory disposal of the three-quarters of a million cubic meters of marine aggregate to be mined during the planned 1974 test. Nevertheless, all principal investigators were funded through a project wrap-up phase, and two were funded long enough to permit them to study baseline conditions in two important aspects of marine life (i.e., benthos, phytoplankton) for a full year. Some final reports were received by NOAA as late as 1976.

The main purpose of this report is to document baseline findings so that the next time a continental shelf sand and gravel mining operation is contemplated, further studies will build on NOMES' experience. Summaries of all principal investigators' final reports are included, as are references to other publications that resulted from the project.

2. BACKGROUND LEADING TO PROJECT NOMES

Sand and gravel, utilized primarily in construction work, but also for the restoration of storm-damaged beaches and for waterfront fill, appear to be the main potential products of continental shelf mining. At present, however, except for a few relatively small operations in bays, tidal rivers, estuaries, and large lakes, most United States sand and gravel aggregate comes from land-based operations. The annual nationwide production is approximately 700 million metric tons. By the year 2000, projections show the probable annual demand to be 3 to 4 billion metric tons (Cooper, 1970). Although inland resources are virtually limitless, there is an imbalance between the distribution of the resources and the markets. Transportation plays an important part in the economics of production; truck transportation for as few as 40 km can double the cost to the consumer. The problems of land production are not limited solely to resource availability and economics. Urban sprawl, zoning laws, and environmental constraints have limited the use of many sand and gravel deposits.

Where metropolitan areas, navigable waters, and favorable marine geology occur in juxtaposition, the continental shelf offers potential for adding to the nation's sand and gravel resource base. This has occurred in Europe, where eight nations annually mine more than 36 million metric tons of sand and gravel from the North and Baltic Seas. The United Kingdom supplies 16% of its need for construction aggregate from offshore. Similarly, Japan mines over 55 million metric tons of sand annually, or 19% of its total needs.

Favorable areas for sand and gravel mining off the United States coast are shown in figure 2. The specific market areas of interest include Boston, New York, Washington, D.C., Norfolk, southeastern Florida, Los Angeles, and San Francisco.

Uncertainty regarding the environmental impact of offshore mining has been a major factor in preventing large-scale sand and gravel mining in the United States, inspiring legal and de facto moratoriums at many levels of government.

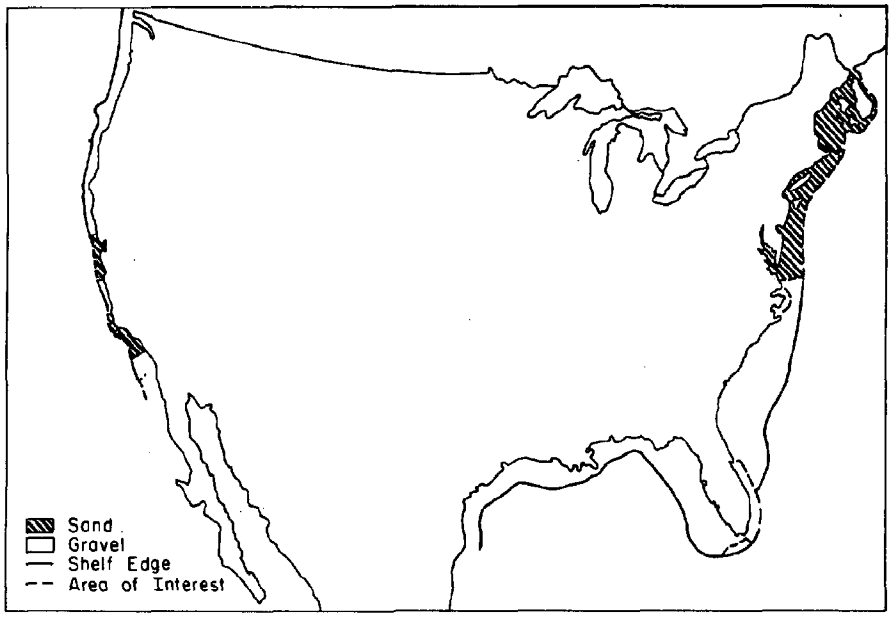


Figure 2. Promising locations for continental shelf sand and gravel mining. (Source: Bureau of Land Management, Draft Environmental Statement, Proposed Outer Continental Shelf Hard Mineral Mining Operation and Leasing Regulations.)

A survey by Battelle Memorial Institute (1971) for NOAA indicated that most environmental research on the effects of dredging has been concentrated in fresh and brackish water. The effect of silt--from channel dredging and onshore placer mining--is one of considerable damage to fish and aquatic vegetation. For several reasons, most past research cannot be directly extrapolated offshore. Organisms in the ocean differ from those in estuaries, lakes, and rivers; sediments are not comparable in composition and organic content; tides and currents affect circulation to different degrees; and marine mining, as a continuous operation, may create more than a brief temporary change in the environment.

NOAA has undertaken extensive studies of the sand and gravel mining industry in the United Kingdom (Hess, 1971). Research in the United Kingdom has centered primarily on the relationship between offshore mining and beach erosion; therefore, few factual data exist on which to evaluate the ecological impact of mining operations.

In the interest of resolving the ecological questions surrounding offshore sand and gravel mining, studies were initiated in Massachusetts Bay by NOAA's Office of Sea Grant and by the Commonwealth of Massachusetts. These were conducted initially by the Raytheon Company, the University of New Hampshire, and the Massachusetts Institute of Technology. Subsequently, additional research capabilities of the NOAA Environmental Research Laboratories as well as those of other Federal agencies and academic institutions were brought to bear on the problem.

Project NOMES drew support and/or advice from the following organizations:

Federal:

Department of Commerce, NOAA
- Environmental Research Laboratories
- National Marine Fisheries Service
- National Ocean Survey
- Office of Sea Grant
- Environmental Data Service
- Coastal Zone Management Task Force

Department of the Interior
- Bureau of Land Management
- U.S. Geological Survey
- Bureau of Sport Fisheries and Wildlife

U.S. Coast Guard

Corps of Engineers
- Office of the Chief of Engineers
- U.S. Army Engineer Division, New England
- Waterways Experiment Station
- Coastal Engineering Research Center

Environmental Protection Agency
- Office of Water Programs
- Office of Research and Monitoring

State:

Commonwealth of Massachusetts, Department of Natural Resources
- Division of Marine Fisheries
- Division of Mineral Resources

Universities and Research Institutions:

Marine Biological Laboratories, Woods Hole
Massachusetts Institute of Technology
Northeastern University
University of California
University of Maryland
University of Massachusetts
University of New Hampshire
University of Rhode Island
Woods Hole Oceanographic Institution

Industry:

Construction Aggregates Corporation
National Sand and Gravel Association
Raytheon Company

Foreign Governments:

National Environmental Research Council, United Kingdom National Research Institute for Pollution and Resources, Japan

Advisory committees were established in order to gain technical oversight and to insure a consideration of local concerns. Committee membership is listed in Appendix A.

3. TECHNICAL PLAN

Many planned investigations were not carried out because of the early termination of the project. However, several studies were funded through completion and form the basis for this report. In addition, an overview of all planned research is presented to assist planners when continental shelf sand and gravel mining is proposed in the future.

3.1 Possible Environmental Impacts

Determining the direct and indirect environmental effects of marine sand and gravel hydraulic mining was the principal objective of the study. The main mining systems of concern were the two types of suction dredging used in Europe: anchor dredging and trailer dredging (fig. 3). The suction hopper dredge ranges in size from about 900 to 9000 metric tons. One or more high-head centrifugal pumps are used to dredge a slurry of solids from the seafloor through suction pipe(s). Dredging by suction is commonplace to about 37 m below the water surface; below that, jet assistance is utilized.

Although the effects of the NOMES operation could not be predicted with certainty, several sources of potential impact inherent in the proposed mining operation were identified (Padan, 1972). A multi-order evaluation of the planned operation is shown in Table 1. Each of the first-order effects (e.g., excavation) is examined and translated into successive orders until it is clear that a given effect is beneficial (+), deleterious (-), or either (+ or -), depending on the specific situation. Table 1 is not meant to be a comprehensive technologic assessment of all the consequences of this type of mining; rather, it is a framework to aid the reader in understanding the relative merits of the NOMES investigations. The following subsections discuss each effect in general, and then treat the NOMES case where possible.

3.1.1 Excavation

The act of obtaining the resource has obvious beneficial aspects in that it broadens the market area's resource base, which in turn helps to hold down construction costs. At the same time pressures on the onshore environment tend to be reduced--in that some portion of the market's construction aggregate is transported by ocean barge rather than by the usual convoy of trucks. Ideally, the potential deleterious effects should be balanced against gains of this sort. An overview of the entire mining cycle is offered in

Table I. Evaluation of Possible Effects of Marine Sand and Gravel Hydraulic Mining

1st Order	2nd Order	3rd Order	4th Order	Beneficial (+) or Deleterious (-)
Excavation	Obtain sand and gravel	Broaden resource base in market area	Hold down construction costs	-
		Reduce pressures to expand onshore sources of supply	Prevent accelerated deterioration of onshore environment	+
			Prevent increase in truck traffic	+
	Change bathymetry	Leave mined-out area pock-marked with pits	Cause formation of stagnant water in pits	-
		Alter beach profile	Cause beach slump	-
		Alter wave refraction pattern	Cause coastal erosion	-
		Alter littoral sand budget		
		Change migration patterns	Harm fishery	-
	Expose boulders	Snag bottom trawls, etc.	Increase fishing expense	-
		Provide hiding areas for organisms	Improve fishing	+
		Provide attachment surfaces for organisms	Increase food supply	+
	Remove Substrate	Destroy benthos	Harm fishery	-
		Destroy spawning ground	Inhibit repopulation	-
	Penetrate fresh water aquifer	Cause discharge of fresh water	Lower onshore water table	-
			Cause saltwater encroachment	-
Discharge plume	Discharge fine sediments at surface	Directly affect marine organisms, including juveniles and larvae	Introduce pollutants	-
			Harm filtering structures	-
			Harm respiratory surfaces	-
			Decrease feeding efficiency	-
		Reduce light level in water column	Reduce photosynthetic production	-
		Increase surface area for bacteria	Reduce O_2 level	-
		Create turbidity	Effect unpleasant appearance	-
	Discharge bottom water at surface	Introduce heavy metals	Harm marine organisms	-
		Introduce nutrients	Encourage plant growth	+ or -
Blanket of fines	Smother benthos	Harm fishery		-
	Inhibit recruitment			
	Smother algae	Reduce food supply		-
	Change character of substrate	Interfere with feeding	Reduce population and/or alter migration patterns	-
		Interfere with locomotion		
		Foul respiratory surfaces		
		Reduce likelihood of larval setting or metamorphosis		
		Recruit new communities		+ or -
	Smother vegetation	Cause soil to destabilize	Redistribute soil where not wanted	-
	Smother coral	Lose habitat		-
	Deposit in unwanted areas	Fill navigation channels		-
		Alter coastline		-

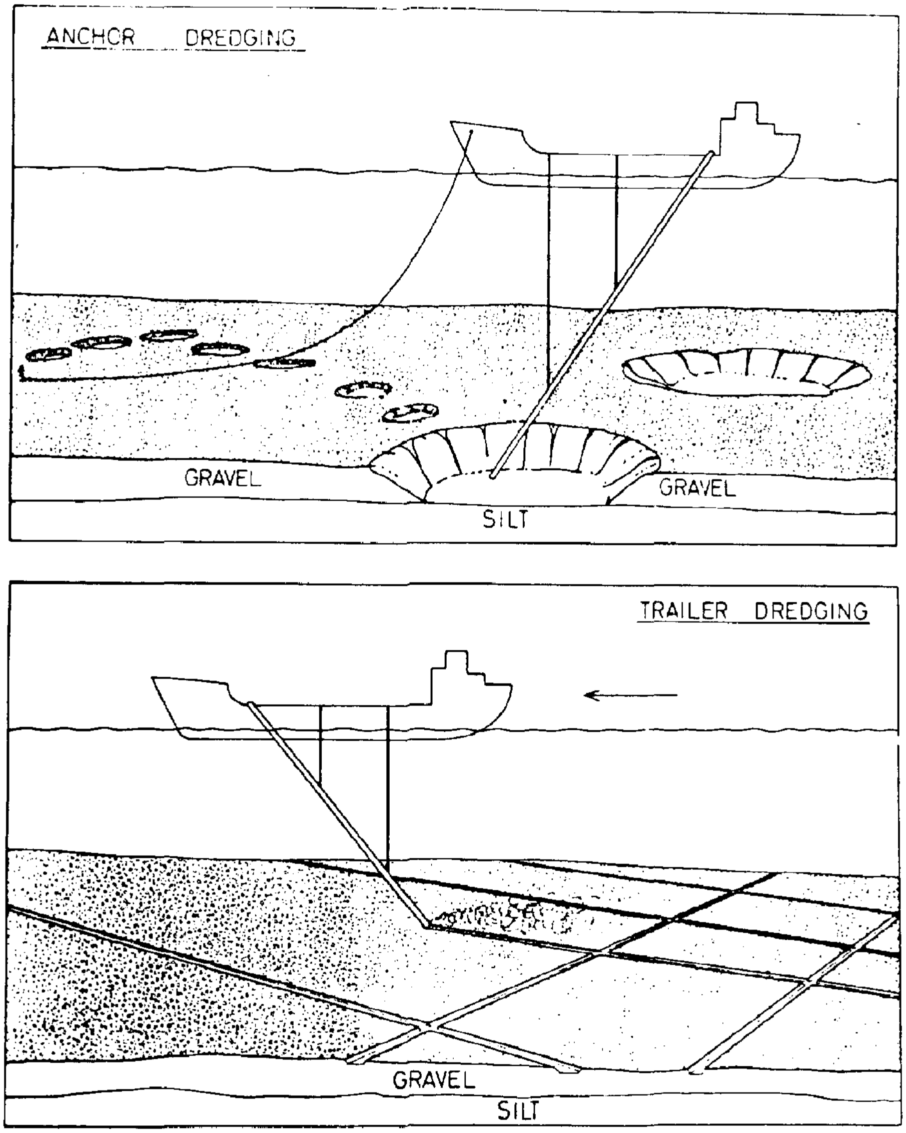


Figure 3. Schematic representation of the two main types of suction dredging on the European shelf. (Source: International Council for the Exploration of the Sea, 1975.)

Appendix B. This report deals only with the excavation stage of the cycle. Details of the full cycle are given by Hess (1971) and the National Research Council (1975).

Initially, excavations in the seafloor are created either in the form of pits or trenches. The planned NOMES operation would have removed sediments hydraulically from one site at a time to produce numerous craters averaging 4 to 5 m in depth. An area of approximately 25 hectares would have been pockmarked in this fashion. Such pits created in the European industry are found not to refill with sediment and frequently develop stagnant water (Hess, 1971).

If close enough to shore, mining could alter the beach profile and cause a drastically slumped beach as has happened in England (R. L. Cloet, Natural Environment Research Council, Taunton, England, personal communication). The NOMES site was far enough from shore to preclude this problem.

The altered bathymetry could change the wave refraction pattern and/or the littoral sand budget. In this case, on the basis of coastal erosion research conducted by its Coastal Engineering Research Center, the U.S. Army Corps of Engineers advised that the planned excavation at the selected site threatened no physical environmental damage to the coastline.

The altered bathymetry could conceivably change migration patterns of some species of marine life.

The heavily cratered seabed may expose boulders that snag bottom trawls, seines, long lines, or scallop dredges (International Council for the Exploration of the Sea, 1975). The same boulders, however, create hiding areas for some species--such as lobster--and provide attachment surfaces for others.

The process of excavation would destroy the benthos as well as any spawning grounds in the immediate area of mining.

It is conceivable that the excavation of craters could result in the penetration of fresh water aquifers important to onshore users. This would result in a release of fresh water to the marine environment, and a lowering of the water table onshore. This could cause saltwater encroachment, thereby contaminating onshore water wells.

3.1.2 Discharge Plume

During hydraulic mining, large amounts of silt are released in the overflow from the dredge. For each cubic meter of sand and gravel extracted, approximately 10 m^3 of bottom also would have been withdrawn during the planned operation. During each of the 60 planned 2-hr mining cycles, approximately 370 m^3 of fine material would have been discharged from the dredge. The plume formed by this discharge would have been heaviest in the immediate vicinity of the dredge.

Assuming that mining would not be permitted at a sand and gravel deposit overlain by polluted sediments, the main concern then becomes the impact of the "clean" plume on marine organisms about which little is known, even though extensive literature exists pertaining to the response of estuarine organisms to high levels of suspended materials (e.g., Sherk and Cronin, 1970).

Evidence of the effects of suspended sediments on estuarine organisms has often been applied to organisms of clearer ocean waters. However, such an application is probably not justified. Ocean organisms in most cases have evolved in response to an environment different from that of the estuaries and have developed the highly efficient filtering mechanisms necessary for removal of particles from a rather sparse nutritive suspension. Introduction of unnaturally high levels of suspended materials can result in direct interference with the function of the filtering structure. Respiratory surfaces are also more sensitive to the higher levels of sediments.

Preliminary observations on the eastern lobster, *Homarus americanus*, indicate that this organism as an adult possesses high tolerance to siltation, at least of an acute nature (S. B. Saila, Grad. School of Oceanogr., U. of Rhode Island, personal communication; Saila et al., 1968). Its presence in embayments, with background levels of suspended solid material far above those found in cleaner coastal waters--generally believed to represent a more "typical" lobster habitat--demonstrates this tolerance. On the other hand, experiments investigating the tolerance of lobster larvae to unnaturally high levels of kaolin clay and finely ground quartz (the former a common component of many nearshore, terrigenous sediments, the latter a common mineral in ocean sediments) indicate that certain developmental larval stages are indeed sensitive to particular size ranges and/or concentrations of suspended materials (Cobb, 1972) and could probably not survive in their presence.

The preceding discussion could be an introduction to the problem faced by fish as well. Although many species would no doubt be driven from the excavation area and the region of suspended silt, certain fishes are known to be attracted to this sort of disturbance, several of which are of particular economic significance. Cod fishermen in regions of New England keep in close touch with mechanical clam digging operators, as the cod is known to be attracted to disturbances of the bottom (Saila, personal communication). Winter flounder exhibit a similar behavior, as do sea robin and sculpin. These fishes are possibly attracted to large numbers of benthic invertebrate organisms stirred up into the waters by the disturbance. But just how long these organisms would remain in the region in the face of mechanical or chemical irritation resulting from the suspended solids is not known.

Most fishes employ some type of mucous system for cleaning the gill tissues which entrap particles of material in the respiratory water. This mucus evidently is ingested by certain fishes. If toxic materials were resuspended from the bottom, it is possible that certain ill effects to the mucus-ingesting fish could result.

Physiological responses to abnormally high levels of suspended materials have been observed to include depression of oxygen transfer across gill tissues and reduction in tissue glycogen levels. These effects, if persistent, can result in increased mortality and impairment of reproductive ability (Sherk, O'Connor, and Neumann, 1972). The particles could also interfere with feeding by those species adapted to visual means of detecting prey.

In the proposed experiment, it was expected that the relatively short time and extent of experimental mining would have insignificantly affected free-swimming fishes in the water column. It would have been necessary, therefore, to determine tolerance of selected species of particular commercial or ecological significance to chronic disturbances, when possible, under controlled experimental conditions. From the results, one might have been able to predict the effects on natural populations.

One of the effects of the discharge plume is associated with the interference of the passage of sunlight resulting from the abnormally high density of suspended solids in the water column. A short-term reduction in photosynthetic production may be directly correlated with reduced light intensity at the surface, within the water column, and, in relatively shallow waters, at the bottom. The relative severity of these effects depends not only on the amount of material introduced by the mining operation, but also on the normal background levels and fluctuations.

The fine particles in the discharge plume offer a great increase in surface area available for the growth of bacteria. This development would reduce the oxygen level in the water column, which, in certain situations, could result in anoxic conditions.

In addition, the turbid appearance of the plume could be considered unpleasant--a factor of particular importance if the plume advects to a recreational area.

The bottom water associated with the plume could contain heavy metals, as could the particles themselves. In either case, the impact on marine organisms could be substantial.

Another important consideration is the possibility of accelerating net photosynthetic production associated with the introduction of nutrients into the waters where they were previously present only in small, growth-limiting quantities. Some workers believe that in coastal waters phytoplankton production is essentially nitrogen-limited for the greater part of the year, and especially during periods of intense spring "bloom" (Yentsch et al., 1971; Yentsch, 1972). Therefore, resuspension of nitrogen-rich bottom sediments could possibly encourage plant growth. Such increases may not necessarily be of net benefit to the marine community or associated commercial activities. An increase in phytoplankton can greatly accelerate silting and fouling of normally clear waters, with associated decreases in other water quality characteristics. In the marine environment, relationships between "red tide" blooms and abnormally high levels of an essential nutrient, previously available only in limiting quantities, are a possibility.

3.1.3 Blanket of Fines

The most serious concern over this type of mining is the effect of the eventual blanket of fine sediment resulting from the redeposition of the fines in the discharge plume. The planned mining operation would have resulted in a significant degree of blanketing extending over the bottom surface some tens of kilometers from the mining barge. Roughly 250 km^2 of the seafloor was expected to be covered by fine sediment to a depth greater than 0.010 mm.

Such a covering can pose several problems. Direct burying and resultant smothering of benthic organisms and algae can occur. Also, the resultant change in particle-size distribution of the bottom sediments may in itself prevent continued habitation by certain species through interference with feeding or locomotion and failure by fouling of respiratory surfaces. In addition, regions can be blanketed with material texturally or chemically unfit for larval setting or metamorphosis. This could result in localized alterations of migration patterns of certain species. It could also result in eventual depopulation of an area through loss of recruitment of young, even though not directly unsuitable for adult organisms. On the other hand, it could result in the recruitment of benthic communities new to the area.

In some cases vegetation could be smothered, which could result in a destabilization of the bottom with a resultant redistribution of bottom sediment to areas where it is unwanted, such as beaches.

A coral reef relatively far from the mining operation could become silted over, causing the lost of a habitat for many fish.

Finally, the suspended sediment could redeposit in areas where it could simply cause nonbiologic problems. For example, navigation channels could become filled, requiring more frequent maintenance dredging. Also, the coastline itself could become altered by the buildup of fine sedimentary particles.

3.2 Research Strategy

The most severe environmental impacts discussed above can be generalized as follows:

- The effects on the benthic habitat caused by sediment removal and redeposition;
- The effects on metabolism and survival of organisms confronted with high suspensions of fine particulate matter;
- The chemical and physical reactions of resuspended bottom deposits;
- Chemical constituent transfer to the water column or sediments, their uptake by organisms, and possible buildup through the marine food web.

It was believed by the Technical Advisory Committee that the major impact would have been caused by benthic alterations and would have been a long-term change--but one that could have been detected by field observations. It was also believed that the direct effects of the mining test would have been so masked by natural variation in the coastal marine ecosystem that any practicable field compaign would have to be targeted at the detection of enormous changes. The subtle direct effects were to have been perceived through laboratory experimentation. Therefore, the approach to these questions was to have involved a synthesis of theoretical, observational, and experimental tasks.

Initially, the proposed experimental mine site and projected impact area were to be described in terms of geologic, chemical, oceanographic, and biologic characteristics. These preliminary observations were to have influenced the detailed design of subsequent laboratory and field experiments.

Theoretical determinations of the dispersion of suspended sediments discharged from the dredge, in conjunction with results obtained from experimental testing of organisms, were to have provided the basis for modeling the degree of stress associated with high sediment levels.

Unless preliminary predictions based on fundamental biological, physical, and chemical research indicated that the proposed mining test was likely to cause extensive environmental damage, models describing the projected ecological impact would have been verified with an experimental mining operation. Following the test period, the reestablishment of affected biologic communities and the general stability of redeposited fines was to have been monitored.

3.3 Premining Investigations Completed

Initial surveys were conducted to characterize the nature and variability of the mine site and projected impact area. These observations constitute a baseline of biologic, geologic, chemical, and physical oceanographic data for the area. To augment these studies, one series of laboratory experiments was completed.

3.3.1 Biological Oceanography

The various biologic communities inhabiting the mine site and impact area were characterized, and the normal seasonal fluctuations of principal organisms were determined, during the year prior to proposed mining operations. On the basis of technical review sessions, the benthos was deemed to be the most sensitive aspect of the ecology as noted above. Phytoplankton populations were sampled to determine their distribution, abundance, and variability.

Experiments with varying levels of suspended sediment were conducted on both marine and estuarine organisms collected from California. Although the studies were not conducted in the NOMES project area, it was planned to utilize an existing facility (in California) to study organisms analogous to those found in Massachusetts Bay.

3.3.2 Geological Oceanography

The geologic character of the mine site was determined through precision close-grid bathymetric mapping, subbottom profiling, grab sampling, and side-scan sonar. Core and grab sampling made possible a determination of the chemical and physical properties of bottom sediments as well as an estimate of the portion of mined aggregate expected to overflow the dredge. Underwater photographic reconnaissance provided data regarding the substrate and, to a limited extent, the characteristics of fauna assemblages with respect to bottom sediment types.

3.3.3 Chemical Oceanography

Extensive data on water quality (temperature, salinity, dissolved oxygen, nutrients, trace elements, BOD, DO, total organic) are available for nearby locations in Massachusetts Bay and were supplemented with additional samples taken at the NOMES site throughout the experimental period. Additional data were also obtained on background levels of suspended sediment and organic matter.

3.3.4 Physical Oceanography

Data on currents were obtained for use in predicting the net transport of suspended sediments (to delineate the sediment impact area) as well as to aid in interpretation of simultaneous measurements and samples of water chemistry and phytoplankton. The basic factors determining the dynamics of the water column in the experimental area are generally understood; however, further empirical data obtained during the particular current regime associated with the dredging period would have been required as input to predictive dispersion models. Drogue and dye studies, as well as a test particle study, were conducted--along with current measurements--to acquire needed data on water mass movements in the NOMES experimental area.

3.4 Investigations Planned But Not Conducted

A number of other studies were planned but were not conducted because of the project cancellation.

3.4.1 Premining Investigations

Within the category of benthic studies, a special effort was to have been addressed to the possible impact of the test dredging on lobsters, since the lobster fishery is important to the Commonwealth of Massachusetts. The objectives of this study were to evaluate the potential impact of offshore sand and gravel mining on lobsters and the lobster fishing industry and to determine the immediate impact of project NOMES on the lobster fishing industry that was operating within the study area.

It had been planned to conduct a limited amount of sampling for zooplankton in order to investigate the relationship between sediments added to the water column by the dredge discharge silt plume and the subsequent energy transfer in the marine plankton ecosystem. The emphasis would have been on laboratory experiments.

Seasonal and monthly changes in species composition, abundance, weight, food habits, size distribution, and incidence of disease of ground-fish were to have been determined by means of three separate trawl tows taken each month at the test site as well as at two control stations. In addition, gill nets were to be set each month to sample pelagic species--both diurnally and nocturnally.

The aquarium turbidity studies noted above were to have been conducted in a Massachusetts Bay aquarium complex as well. Other laboratory investigations were to have involved effects of the discharge plume on phytoplankton, benthic algae, zooplankton, and finfish.

3.4.2 Experimental Mining

The mining test had been scheduled for a 6-week period in late spring 1974. This period was selected to coincide with the sensitive "bloom" period of phytoplankton to learn whether or not mining would have any impact on this phenomenon.

The dredge selected for the field operation was the 27,000-metric-ton "Hydrobarge" *Ezra Sensibar* (fig. 4). The 155-m-long, 23-m-wide hopper-type barge is both self-loading and -unloading and has a capacity of 12,000 m^3. Mining is accomplished through suction provided by two 84-cm centrifugal dredge pumps amidships. Valving directs the incoming slurry (composed of about 10 m^3 of water for each cubic meter of aggregate) to individual hoppers. Suspended sediments are allowed to overflow the hoppers as each is filled with aggregate.

The bathymetry of the selected site is such that excavations were possible over the full range of deposit depths of 3 to 6.7 m--typically about 4.6 m. A total of three-quarters of a million cubic meters of material was to have been removed over the 6-week experimental period from a deposit distributed over approximately 25 hectares. The dredge was to have conducted three 2-hr operations every 2 days. About 14 hr may have been required between operations for transit, offloading, and return, depending on the distance to the discharge point.

Mining operations were to have been monitored to determine the change in bottom topography, the solids content, size distribution and volumetric overflow of suspended sediment, and the progress of the sediment concentration in the resulting plume of material discharged from the barge. The silt

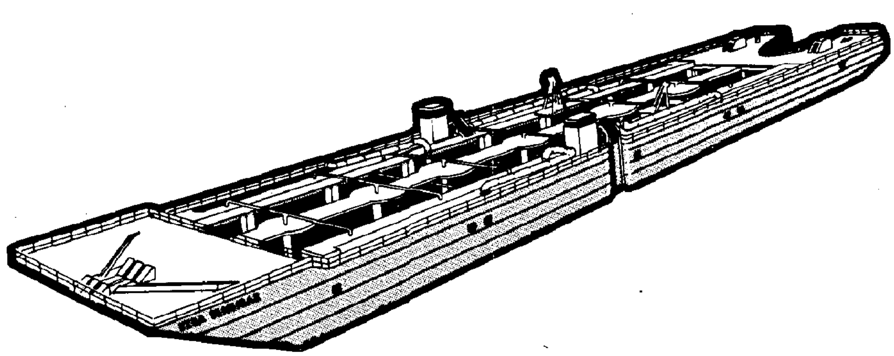


Figure 4. Hydrobarge Ezra Sensibar.

plume was to have been sampled twice a week during the period of mining, and the water quality examined. In addition, the suspended particulates were to have been analyzed for total weight, organic fraction, inorganic fraction, grain-size distribution, and trace metals.

Tide meters were to have been placed seaward of the test site and their readings keyed into drogue studies, current-meter readings, and water sediment photographs, all used to determine and interpret the space-time fate of the plume.

To insure against future charges of indifference to beach erosion caused by the test (as noted earlier, none was anticipated) a modest program was planned to survey the bottom topography in and around the test site. The survey was to have two goals: establishing the size and shape of the dredge pits, as well as their rate of natural fill-in; and predicting the slightest chance, however remote, that the mining activity could alter the wave refraction pattern enough to effect coastal erosion (and/or unwanted deposition). Bathymetric profiles were to be run in eight directions, radiating out from the dredge site toward all eight points of the compass. The length of each run was to be to the beach, where applicable, or to a distance away from the mine site equal to three times the diameter of the site. One set of measurements was to be run during July-August 1973, one during January-February 1974, one after each of two winter storms, and immediately before and immediately after the mining test. Precision checks were to be made by running reverse headings immediately after each run. In addition, side-scan sonar and bathymetric profiles were to be run on a 30-m grid pattern over the dredge site immediately before and after the test.

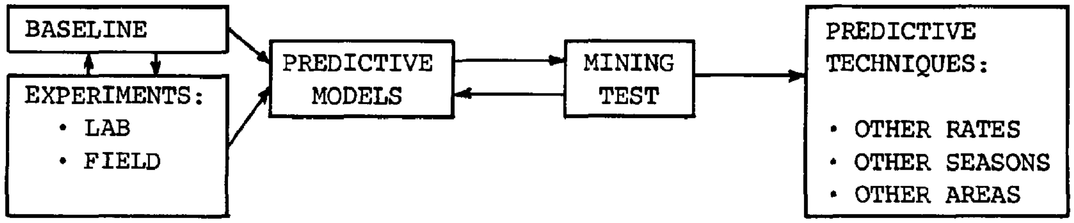
In addition to the tracking and sampling of the silt plume and survey of seafloor configuration, biologic baseline sampling was to be stepped up in frequency during mining. Also planned were studies of phytoplankton, zooplankton, pelagic and demersal fish, fish larvae, benthic invertebrates, benthic larvae, benthic algae, and lobsters.

3.4.3 Postmining Investigations

After the planned period of experimental mining, baseline-type studies were planned for 2 years in order to learn how mining-induced changes in the water column and in the seafloor are altered by natural processes. Of particular concern were the nature and the rate of repopulation of the benthos near the mine site, where the silt plume's blanket of fines was expected to cause mortality.

3.4.4 Predictive Capability and Environmental Guidelines

The desired capabilities to be developed were those of predicting the effects of mining, at that same location, at other rates of production, and on the basis of laboratory findings, during other seasons of the year. Successful tests on analogue organisms would have provided some capability of predicting effects of mining in other areas of the U.S. continental shelf. The planned development of these predictive capabilities is shown below in conceptual form.



4. STUDIES COMPLETED

Studies completed produced a baseline of biologic, geologic, chemical, and physical oceanographic observational data, plus data from one series of laboratory experiments.

4.1 Biological Oceanography

These studies dealt mainly with benthic organisms and phytoplankton. Although other planned biological studies were not carried out, annual values of the commercial fisheries catch in Massachusetts were compiled as one basis for planning additional investigations. In recent years, that value has been about $50 million. With varying rank from year to year, yellow-tail flounder, sea scallop, cod, haddock, lobster, and black-back flounder had the top values during the years investigated (Table 2).

4.1.1 Benthos

The major difficulty in predicting the impact of marine sand and gravel mining on benthic communities is that very little is known about the dynamics of the communities. However, there are several specific effects of concern. For example, silt deposits can smother benthic organisms and inhibit recruitment of their juvenile stages (Wilson, 1954; Scheltema, 1961; Thorson, 1966; Grigg and Kiwala, 1970; Saila et al., 1972; Meadows and Campbell, 1972).

*Table 2. Massachusetts Fishery Value in Millions of Dollars**

	1971	1970	1969	1968	1967
Yellow-tail flounder	6.89	8.66	7.58	6.00	4.96
Sea scallop	5.84	5.78	5.46	8.62	5.27
Cod	5.55	4.85	4.26	2.95	3.16
Haddock	5.32	5.73	7.56	8.04	10.84
Lobster	4.20	5.85	4.74	3.14	2.87
Black-back flounder	2.34	2.35	2.13	1.58	1.96

*Statistics for 1971 and 1970 from Commonweath of Massachusetts (1971).
Statistics for 1969 from Massachusetts Division Marine Fisheries Catch Data.
Statistics for 1968 and 1967 from Commonwealth of Massachusetts (1968).
All lobster statistics from Massachusetts Division of Marine Fisheries Catch Data.

Both benthic and pelagic filter-feeding animals may find extreme difficulty in maintaining metabolic efficiency under conditions of high turbidity (Davis, 1960; Loosanoff, 1961; Rhoads and Young, 1970). As a result of a decreased feeding efficiency, there could well be decreases in growth rate, physiological state, sexual maturation, and number of viable gametes. One might expect the following types of change to occur: (1) a decrease in the number of taxa (Grigg and Kiwala, 1970); (2) a decrease in biomass (g/m^2), and/or primary productivity; (3) modifications of seasonal and spatial successions of organisms (Reish, 1957, 1961; Shar and Mulligan, 1977); and (4) emergence of photosynthetic organisms (Cronin et al., 1971; Taylor et al., 1964).

Large-scale removal of sand deposits will change the bottom topography and therefore the currents and substrate characteristics, all of which affect species composition of communities. Over time, substrate removal is the most threatening to benthic communities since the species composition of a community is primarily determined by substrate characteristics (Thorson, 1946, 1957, 1966; Sanders, 1958, 1960, 1968; Harrison and Wass, 1965; Nichols, 1970; Howell and Shelton, 1970; Bacescu, 1971; Rhoads and Young, 1971; Rhoads, 1974; Young and Rhoads, 1971; Tenore, 1972; Holme and McIntyre, 1971; Meadows and Campbell, 1972; Gray, 1974). Other factors such as currents (Sanders, 1960) and depth (Thorson, 1957; Sanders, 1968; Lie and Kelley, 1970; Golikov and Scarlato, 1973; Dayton et al., 1974), which manifests itself in differences in light penetration and temperature fluctuation, also affect community composition.

Recent studies in France (Cressard, 1975) show that unless the mined area returns to its premining state the community that recolonizes the mining site will be different from the premining community. Studies have been done describing community development at dredge spoil dump sites (Saila et al., 1972; Sykes and Hall, 1970; Tenore, 1972) and after natural die-offs due to red tides (Bloom et al., 1972), but relatively little information is available on the reestablishment of communities in areas where mining has taken place (Sykes and Hall, 1970; Battelle Memorial Institute, 1971).

The benthic community study had several objectives:

1) To describe the general structure and dynamics of the communities in the four major habitats--rock, cobble, sand, and mud--that occur in Massachusetts Bay at or near the NOMES site.

2) To select a series of species or species groups that are characteristic of specific substrate types, and to determine if it is possible to use them as indicator species in environmental studies.

3) To develop predictive models on the effects of marine mining for use in developing guidelines for future commercial mining operations.

4) To test and evaluate procedures for sampling and analyzing benthic communities in order to suggest guidelines for future studies.

Sampling stations

By the summer of 1973, when NOMES was terminated, the benthic community study had progressed to the point where a series of permanent stations had been selected and had been sampled monthly for varying periods of time up to 8 months.

The need to evaluate sampling procedures as well as to understand the dynamics of the communities being studied and the roles of possible indicator species in their respective communities dictated direct visual observation and sampling where feasible. Therefore, scuba techniques became a major feature of the fieldwork, and stations had to be within diving depths--a maximum of 40 m. It was also necessary that they be representative of the major substrate types in Massachusetts Bay. The experimental stations had to be close enough to the mine site to be affected by siltation from the dredge operation and the control stations far enough away to be free of impact. Also, the current pattern around the mine site varied to such an extent that the site had to be bracketed with stations to ensure impact by the planned test mining operation.

The stations selected for use in the study are shown in figure 5. Characteristics such as depth and substrate type are listed in Table 3; Table 4

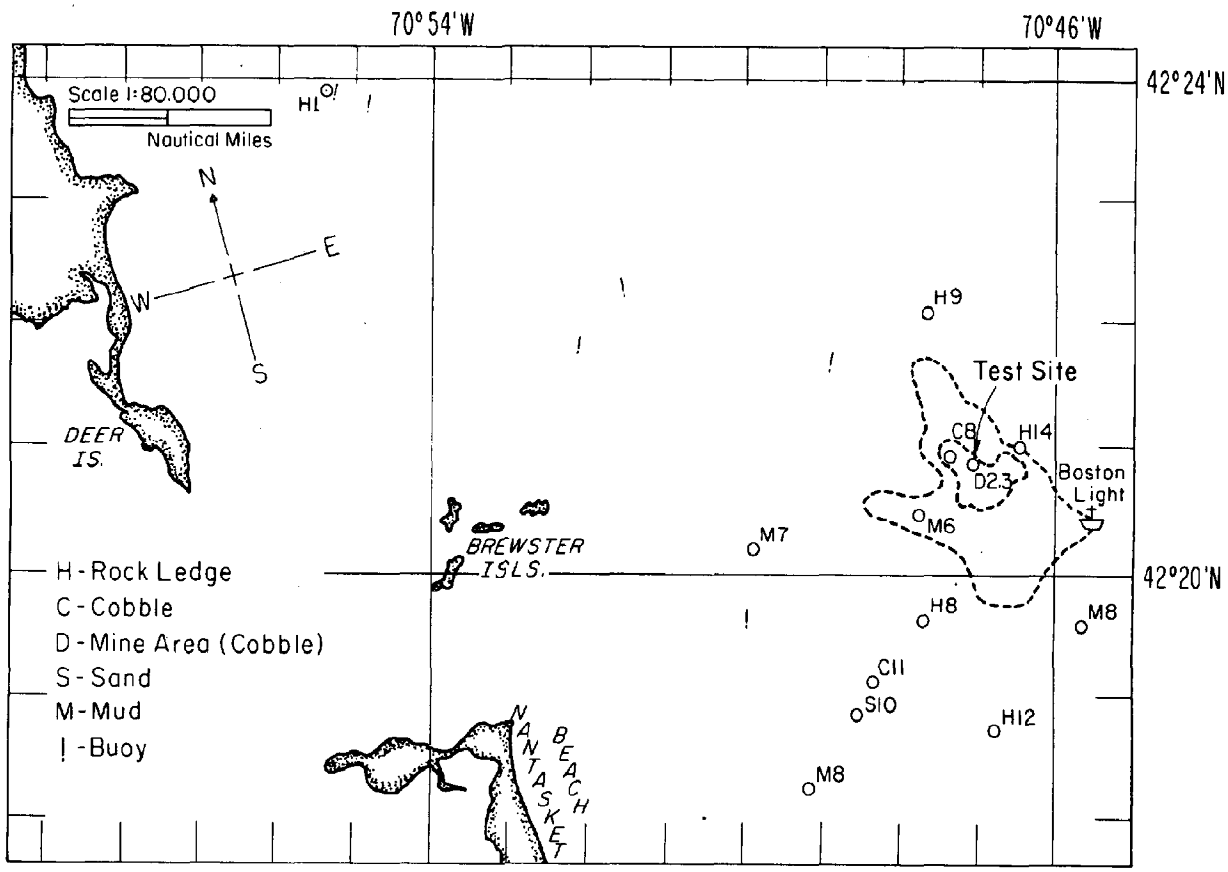


Figure 5. Stations selected for the benthic community study in Massachusetts Bay, identified by substrate type and number.

Table 3. Characteristics of Permanent Benthic Sampling Stations

Site	Distance and Direction from Dredge Site	Depth	Substrate	Silt Cover
Hard 1	7 miles NW	15m	large rock outcropping	clean
Hard 8	1.4 miles SSW	17m	cobble and large boulders	moderate silt
Hard 9	1.5 miles NNW	25m	cobble and large boulders	moderate silt
Hard 12	2.5 miles SE	18m	cobble and large boulders	moderate silt
Hard 14	0.5 miles NE	25m	cobble and large boulders	clean
Cobble 6	within dredge area	32m	gravel with large rocks	clean
Cobble 11	2.2 miles SSW	27m	gravel	heavy silt
Mud 6	0.5 miles SW	35m	mud	heavy silt
Mud 7	2.1 miles SW	28m	mud	heavy silt
Mud 8	1.8 miles SSE	40m	gravel with mud matrix	heavy silt
Mud 9	3.25 miles SSW	18m	muddy sand	heavy silt
Sand 10	2.5 miles SSW	23m	sand	moderate silt

Table 4. Sediment Composition Analyses For The Soft-Substrate Stations in the Benthic Community Study

		January 1973			April 1973			June 1973			Mean for All Months		
Station	Core No.	% Sand	% Silt	% Clay	% Sand	% Silt	% Clay	% Sand	% Silt	% Clay	% Sand	% Silt	% Clay
M6	1				29.0	44.8	26.2	44.1	35.1	20.9			
	2				61.0	24.4	14.6	51.8	32.5	15.7			
	Mean				45.0	34.6	20.4	47.9	33.8	18.3	46.5	34.2	19.3
M7	1	80.1	15,6	4.3	79.5	14.8	5.6	68.5	23.6	7.9			
	2	82.1	14.0	3.9	82.4	11.5	6.1	82.8	11.4	5.8			
	3	77.5	17.1	5.4									
	4	78.7	16.0	5.3									
	Mean	79.6	15.7	4.7	81.0	13.2	5.9	75.6	17.5	6.8	78.7	15.5	5.8
M8	1	65.1	24.8	10.1	54.0	43.9	2.2	67.5	23.8	8.7			
	2	67.7	20.8	11.5	62.6	26.6	10.8	78.9	15.5	5.6			
	3	70.0	19.2	10.8									
	Mean	67.6	21.6	10.8	58.3	35.2	6.5	73.2	19.7	7.2	66.3	25.5	8.2
M9	1				95.4	2.6	2.0						
	2				94.6	3.2	2.2						
	Mean				95.0	2.9	2.1				95.0	2.9	2.1
S10	1				99.2	0.2	0.6	78.7	20.9	0.4			
	2							98.6	0.7	0.7			
	Mean				99.2	0.2	0.6	88.7	10.8	0.5	93.9	5.5	0.6

summarizes the sediment analysis data for the soft substrate stations. The variations in depth and silt cover for similar substrate types within limited distances indicate the heterogeneous nature of the area. From the sediment analyses for a single station, it is clear that there is consistent variability in substrate composition within limited areas.

The total species list for the permanent stations used in this study also reflects the heterogeneous nature of Massachusetts Bay fauna. Over 650 species of benthic invertebrates were identified during the study (Appendix C, Tables C1, C2, and C3). Most of them were found in more than one substrate type. The complexity of benthic populations is demonstrated by the observation that within-station variation from month to month was often as great as between-station variation in any particular month.

Hard substrate communities

Hard substrate includes outcrops of bedrock as well as very large boulders and cobbles. These communities are the most complex to study because a majority of the organisms are permanently attached to the substrate, and this renders them difficult to sample and analyze in a quantitative way. Because of this, most attention was directed to the motile fauna (Tables 5-8, C4, C5).

The complexity of the habitat results in high numbers of species and particularly high numbers of small invertebrates, as can be seen in Table 5. There was up to a factor of 2 variation in the number of species in a sample from month to month and an order of magnitude difference in the densities of total motile species. In fact, the variation at each station from month to month was the most consistent finding.

Table 5. Total Numbers of Species (Parts a. and b.) and of Densities (Part c.) of Benthic Invertebrates

a. Total number of invertebrate species collected on each cruise at each station.

Station	Cruise No.								Mean
	14	15	16	17	18	19	20	21	
H1	51	89	6	6					38.0
H8		87	87	105	146	106	138		111.5
H9		131		99	145				125.0
H12				60	92	64	112		82.0
H14		121	66	92		134	142		111.0
C6		37			81	76	66		65.0
D2			31						31.0
D3				113					113.0
C11				109	78	90	80		89.25
M6	62		67	61	52	79	81		67.0
M7			65	56	29	60	57		53.4
M8			81	73	56	70	68		69.6
M9			78	59		79	88	98	80.4
S10			90	42	58	67	76		66.6

Table 5. (Continued)

b. Total number of motile species collected on each cruise at each station.

Station	Cruise No. 14	15	16	17	18	19	20	21	Mean
H1	31	65	6	6					27.0
H8		57	73	75	104	73	102		80.7
H9		85		77	109				90.3
H12				47	70	54	95		66.5
H14		75	58	67		97	120		83.4
C6		32			73	73	59		59.25
D2			31						31.0
D3				101					101.0
C11				101	75	83	74		83.25
M6	52		56	55	42	72	77		59.0
M7			57	52	26	57	50		48.4
M8			77	68	48	64	65		64.4
M9			71	56		72	82	83	72.8
S10			86	42	49	62	74		62.6

c. Total numbers/m^2 of motile species for each cruise for each station.

Station	Cruise No. 14	15	16	17	18	19	20	21	Mean
H1	4517.0	7182.1	528.0	1148.0					3343.8
H8		3616.2	10728.9	6295.9	13938.9	11146.2	8427.4		9025.6
H9		3080.8		7814.4	7611.4				6168.9
H12				3096.0	12236.8	4394.1	11513.0		7810.0
H14		2446.2	2816.0	3896.2		7374.6	5043.6		4315.3
C6		479.6			4465.0	3497.5	4112.9		3138.8
D2			1640.0						1640.0
D3				4120.0					4120.0
C11				5715.0	2427.5	11140.0	10859.5		7535.5
M6	2231.6		735.7	3262.3	1039.1	2030.9	5792.8		2515.4
M7			643.9	920.0	305.5	1254.6	762.0		777.2
M8			2977.0	2046.1	336.4	639.7	2139.6		1627.8
M9			2666.8	2426.4		3961.5	5410.4	7397.2	4372.5
S10			2261.1	1415.9	1123.8	1914.7	1690.4		1681.2

Table 6. Rankings of the Most Common Motile Benthic Species, Based on the Mean Number of Animals and Grouped by Sampling Station Substrate Type

Hard Substrate Stations:	H1	H8	H9	H12	H14
Number of Times Sampled:	3	6	3	4	5
Spirorbis spirillum	3	1	1	1	1
Spirorbis borealis		2	2	2	2
Caprella septentrionalis	1	3		4	4
Modiolus modiolus	2	4			
Ischyrocerus anguipes	9	5	5	8	9
Pontogeneia inermis	7	6		3	
Ophiopholis aculeata		7	6		6
Tonicella rubra		8	8	7	10
Achelia spinosa		9			
Cucumaria frondosus		10			
Jassa fulcata	4				
Caprella linearis	8				
Lacuna pallidula	6				
Nereis pelagica	5				
Lepidonotus squamatus	10				
Spirorbis violaceus			7		
Musculus niger			9		
Sympleustes glaber			3		8
Metopella angusta			4		
Strongylocentrotus droebachiensis			10	6	5
Pectinaria granulata				9	
Anomia simplex				10	7
Lacuna vincta				5	
Balanus balanoides					3

Cobble Substrate Stations:	C6	T2	T3	C11
Number of Times Sampled:	4	1	1	4
Euclymene collaris	1	1	1	2
Unicola irrorata	2		3	1
Exogone dispar	3	7	2	3
Glycera capitata	4	4	10*	
Strongylocentrotus droebachiensis	5		8	
Phyllodoce mucosa	6		7	8
Ischnochiton alba	7		10*	
Spio setosa	8	10		
Corophium crassicorne	9		4	
Euchone rubrocincta	10	9		7
Phyllodoce groenlandica		2		
Syllis armillis		3		
Tharyx acutus		5		5

Table 6. (Continued)

(Continued) Cobble Substrate Stations:	C6	T2	T3	C11
Number of Times Sampled:	4	1	1	4
Owenia fusiformis		6		6
Pholoe minuta		8		
Spirorbis spirillum			5	
Spirorbis borealis			6	
Moelleria costulata			9	
Notomastus luridus				4
Aricidea jeffreysii				9
Nephtys ciliata				10

	Mud			Sand	
Soft Substrate Stations:	M6	M7	M8	M9	S10
Number of Times Sampled:	6	5	5	5	5
Ninoe nigripes	1	1	2		
Maldane sarsi	2				
Spio setosa	3		1		
Sternaspis scutata	4				
Nucula delphinodonta	5		9		
Scoloplos fragilis	6	3	5	7	
Travisia carnea	7				
Edotea montosa	8	2	4		
Pholoe minuta	9	10	3	6	
Periploma papyratium	10				
Diastylis sculpta		4		8	10
Nephtys ciliata		5			6
Owenia fusiformis		6		1	
Modiolus modiolus		7		2	3
Photis reinhardi		8		4	
Nassarius trivittata		9			
Thracia myopsis			6		
Asarte undata			7		
Cerastoderma pinnulatum			8		
Paraonis gracilis			10		
Pseudunciola obliqua				3	2
Tharyx acutus				5	
Aricidea jeffreysii				9	
Phyllodoce mucosa				10	
Euclymene collaris					1
Nephtys incisa					4
Spiophanes bombyx					5
Jassa falcata					7
Edwardsia elegans					8
Unciola irrorata					9

Table 7. Mean Ranking of Numerically Dominant Taxonomic Groups, Arranged According to Substrate Types

Taxonomic Group	Hard Substrate				
	H1	H8*	H9	H12	H14
Polychaeta	2.5	1.0	1.0	1.0	1.0
Amphipoda	1.25	2.5	2.0	2.25	2.8
Bivalvia	2.0	3.7	2.0	3.75	2.8
Gastropoda	3.7	4.7	5.0	4.0	4.6
Asteroidea	4.0	5.0	6.0	6.75	9.2
Ophiuroidea	5.5	6.2	3.5		5.75
Polyplacophora	9.5	6.8	6.2	4.25	6.0
Holothuroidea	6.5	7.25	11.3	10.0	11.0
Pantopoda	7.0	7.8	8.3	9.5	9.5
Isopoda	8.0	8.0	10.5	10.25	10.5
	Cobble Substrate				
	C6*	C11			
Polychaeta	1.0	1.25			
Amphipoda	2.0	1.75			
Ophiuroidea	3.0	9.0			
Echinoidea	3.75	7.5			
Bivalvia	4.0	3.25			
Polyplacophora	5.25	5.0			
Gastropoda	5.5	4.0			
Anthozoa	7.0	8.0			
Brachyura	7.0	10.0			
Sipunculida	7.0				
	Mud Substrate				
	M6*	M7	M8	M9	
Polychaeta	1.0	1.0	1.0	1.0	
Bivalvia	2.0	2.8	2.4	3.0	
Isopoda	3.2	2.8	2.8	5.0	
Amphipoda	4.3	4.2	3.8	2.0	
Gastropoda	4.8	5.8	5.8	6.2	
Cumacea	5.2	4.4	5.4	4.6	
Anthozoa	7.0	7.0	7.2	6.2	
Brachyura	7.0	8.0	8.0	8.0	
Asteroidea	7.0	8.0	7.3	8.0	
Aplacophora	7.25		5.0		
	Sand Substrate				
	S10*	M9			
Polychaeta	1.2	1.0			
Amphipoda	1.8	2.0			
Bivalvia	3.0	3.0			
Cumacea	5.2	4.6			
Anthozoa	5.4	6.2			
Gastropoda	5.6	6.2			
Isopoda	6.8	5.0			
Polyplacophora	7.0				
Echinoidea	7.4	7.25			
Holothuroidea	7.5	9.3			

Table 8. Mean Ranking of Feeding Types, Grouped According to Substrate Types

Feeding Types*	Hard Substrate H1	H8	H9	H12	H14
Supension/Filter[1]	2.0	1.0	1.0	1.0	1.0
Scraper/Omnivore[2]		2.0	2.0	2.3	2.0
Suspension/Predato[3]	1.5	3.6	5.0	4.3	3.3
Predator/Epi/Micro[4]	3.0	4.0	4.0	4.3	4.8
Scraper/Herbivore		5.8	5.5	4.5	5.0
Predator/Epi/Macro[5]	2.5	5.8	6.0	6.5	8.0
Deposit/Indirect[6]		6.2	5.0	5.0	5.5
Parasite		7.8	7.5	8.8	9.8
Deposit/Direct[7]		8.8	8.5	10.3	9.2
Predator/In/General[8]		10.2	10.5	8.8	9.5
Predator/Epi/Scraper[9]	3.0	10.8	9.5	10.0	10.0
Predator/In/Mollusc[10]		12.0	12.0	11.8	10.0

	Cobble Substrate C6	C11
Scraper/Omnivore	1.3	1.0
Deposit/Indirect	4.0	2.5
Deposit/Direct	1.6	3.0
Suspension/Filter	5.0	4.0
Predator/Epi/Micro	3.0	5.0
Predator/In/General	6.0	5.3
Scraper/Herbivore	7.0	7.5
Suspension/Predator	8.3	8.0
Predator/Epi/Macro	9.3	8.0
Parasite	11.0	9.3
Predator/In/Mollusc	9.3	10.0
Predator/Epi/Scraper	10.3	10.3

* Key
1 filters suspended particles
2 bites or rasps attached plants and animals
3 captures suspended animals
4 predator on small motile epifauna
5 predator on large motile and sessile epifauna
6 sorts out small particles of sediment to ingest
7 ingests sediment as it burrows
8 nonspecialized predator on infauna
9 rasping predator on sessile epifauna
10 predator on infaunal molluscs

Table 8. (Continued)

Feeding Types	Mud Substrate M6	M7	M8
Deposit/Direct	1.6	6.0	5.4
Deposit/Indirect	1.8	3.2	1.8
Predator/In/General	2.6	1.0	3.0
Suspension/Filter	4.2	3.0	2.8
Scraper/Omnivore	5.0	2.8	3.6
Predator/Epi/Micro	5.6	5.4	4.6
Predator/In/Mollusc	6.6	7.6	9.2
Suspension/Predator	7.6	6.8	8.0
Predator/Epi/Macro	7.6	7.2	8.0
Scraper/Herbivore	7.8	7.6	7.2
Parasite	8.2	7.2	8.4
Predator/Epi/Scraper	8.2	7.6	9.0
	Sand Substrate M9	**S10**	
Deposit/Direct	6.3	1.2	
Scraper/Omnivore	2.0	1.8	
Suspension/Filter	3.0	4.0	
Predator/In/General	4.8	4.0	
Deposit/Indirect	1.0	4.2	
Predator/Epi/Micro	4.3	5.8	
Predator/In/Mollusc	6.8	7.0	
Predator/Epi/Macro	8.3	8.4	
Suspension/Predator	8.8	8.6	
Scraper/Herbivore	8.8	8.8	
Predator/Epi/Scraper	8.8	9.0	
Parasite	8.5	9.2	

Cobble substrate communities

The cobble stations selected were primarily small cobbles and gravel intermixed with a few larger rocks, some more than a meter in diameter. The larger rocks have sessile fauna and flora similar to those found at the hard substrate stations (see Table C1). The dominance of polychaetes and amphipods is not surprising considering their small size and the number of species to be found in each group. The high ranking for scraper/omnivores at the cobble stations is due to classification of most amphipods as scraper/omnivores.

Soft substrate communities

The soft substrate communities were found in sand and mud. Tables 3 and 4 summarize the general characteristics of the stations for these communities. Stations S10 and M9 were most closely related to the cobble stations because there is considerable overlap in infaunal species composition.

The soft substrates appear to be the most homogeneous on casual observation because there are no obvious changes in substrate morphology. However, the variation in species composition at each station from month to month was very high with the species numerically dominant one month being absent or in insignificant numbers the next month.

General comparisons

There are two ways to organize the results of the monthly sampling at a series of permanent stations. Most of the results presented summarize and average the data in an attempt to give an overview of the different communities being studied. With this approach it is possible to compare community types and to relate them to substrate types. Hard substrate communities are dominated by suspension feeders. The scraper/omnivore group is composed primarily of amphipods that are associated with the suspension feeders. In spite of a considerable standing crop of macroscopic algae, there are relatively few species that are herbivorous. The soft substrates are dominated by deposit feeders and their predators. Amphipods that are particle feeders are common also.

Polychaetes, amphipods, and bivalves are the numerically important groups with isopods replacing amphipods at those soft-sediment stations with a high clay content. The species tend to change with the substrate type, but not with a clear correlation. This is a heterogeneous environment and only a minority of the species appeared to be specialists for substrate type (see "Cluster analyses and selection of indicator species" below). The sampling scheme was biased toward small motile forms on all substrate types.

Table 6 clearly demonstrates the complexity of even the seemingly simple mud and sand communities; the variation in numerical ranking of the most common species was very high. Furthermore, density differences from month to month could be measured in orders of magnitude (see Table C5). Month-to-month variability was consistent for all stations. Therefore, it was not due to sampling problems for a particular substrate.

Species diversity

Species diversity indices are regularly used in environmental impact studies to determine whether there are changes due to manmade influences. The most commonly used index is the Shannon-Wiener information theory (Shannon and Weaver, 1963). Diversity indices were calculated for all stations each month and are recorded in Table 9. As with species rankings, the variation in diversity values from month to month at a single station was often greater than between stations in a single month. Peet (1975) has shown that all diversity measures are sample-size-dependent, but even with uniform sampling procedures and sample numbers, there were great differences in the species composition as well as the relative and total numbers at a given station from month to month (Table 5). There were no consistent differences in diversity values between substrate types or even between stations on the same substrate type. Station H14 had high (>3.0) values in three separate months, but these bracketed values of 2.373 and 2.666, which are only average, and the 2.666 value occurred when the density per square meter was highest for the station and the number of species found was second-highest.

Table 9. Shannon-Wiener Diversity Indices (H') For All Samples Analyzed For All Stations

Station	Cruise No.							
	14	15	16	17	18	19	20	21
H1	2.067	2.632	0.778	0.752				
H8	0.525	2.833	2.531	2.284	2.327	2.944	2.509	
H9		3.225		2.357	2.723		2.679	
H12				1.857	1.647	2.209		
H14		3.354	3.137	2.373		2.666	3.698	
C6		2.720			2.031	2.612	2.169	
D2			2.056					
D3				3.184				
C11				3.160	3.248	1.968	1.938	
M6	2.502		2.757	2.430	2.169	2.952	2.669	
M7			2.692	2.746	1.896	2.932	2.567	
M8			2.373	2.403	2.933	3.015	2.316	
M9			2.818	2.319		2.862	2.787	2.771
S10			2.161	1.770	2.169	2.274	2.548	

Note: Only motile species for which there were numerical data were used.

A second type of diversity measure was also used because it appeared to contain more information for comparing stations. The rarefaction method described by Sanders (1968) gives a graphic display that describes the increase in number of species as the sample size increases as well as the increase in the total number of animals and of species in the sample. Sanders used only polychaetes and bivalves and worked with soft substrate communities. Rarefaction curves for all motile species were plotted for all stations from cruises 17, 18, 19, and 20 (figs. 6-9). Rankings based on

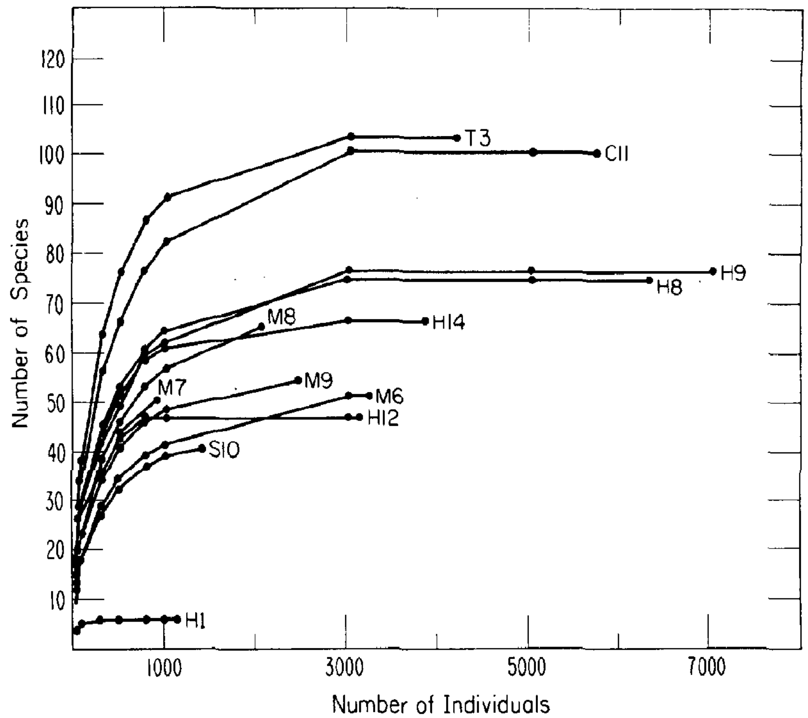


Figure 6. Rarefaction curves for Cruise 17, May 1973.

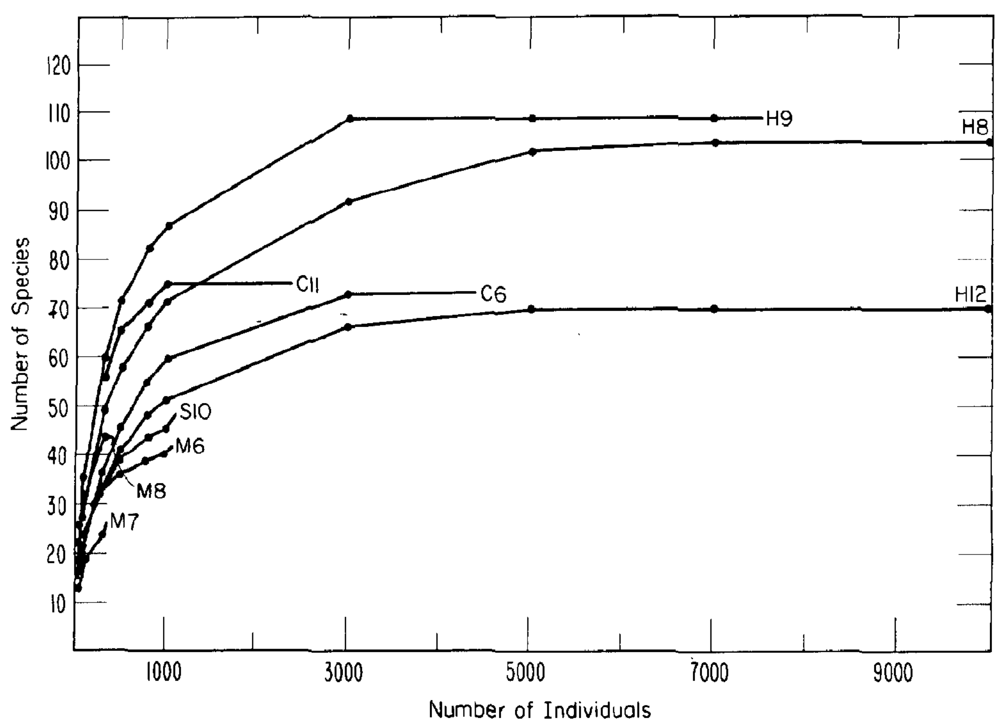


Figure 7. Rarefaction curves for Cruise 18, June 1973.

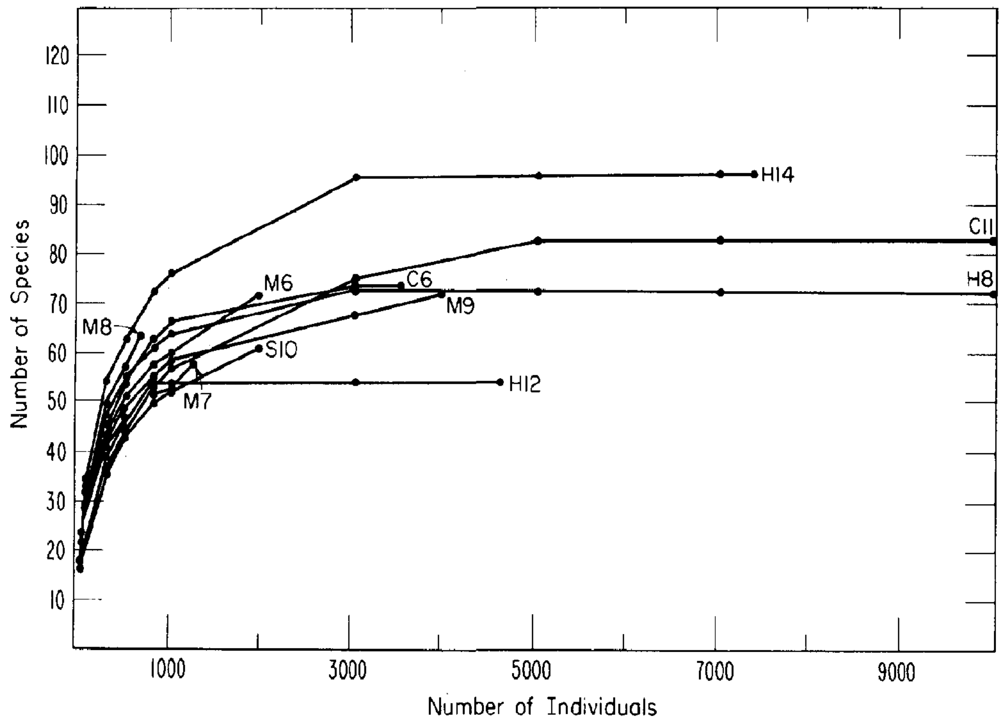


Figure 8. Rarefaction curves for Cruise 19, July 1973.

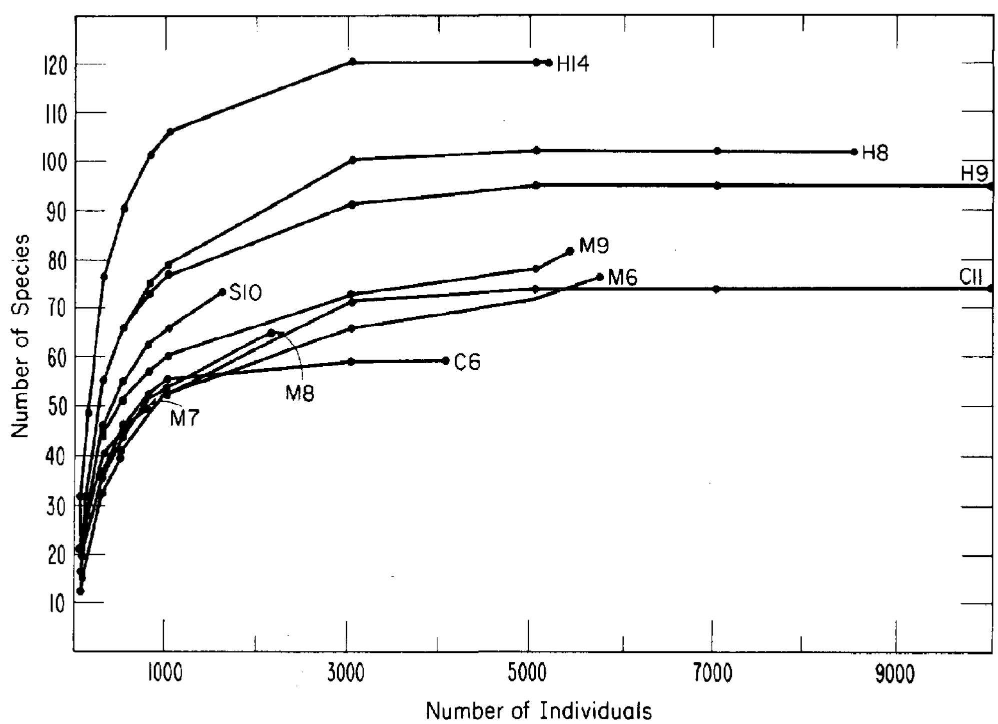


Figure 9. Rarefaction curves for Cruise 20, August 1973.

these curves are presented in Table 10. The cobble and hard substrate stations, with the exception of H12, tend to rank highest in the four cruises because they had both the highest densities and highest total number of species. It must be remembered that the cobble and hard substrate stations, because of their variety of subhabitats, have the greatest surface area available for small motile forms; this is particularly true for the rock stations where the red algae provide a complex surface that serves as a refuge for large numbers of species.

Rarefaction curves for one or more taxonomic groups were generated to determine if any might be useful alone or in combinations, since total analysis of samples is very time consuming. Sanders (1968) used polychaetes and bivalves. Table 11 summarizes the station rankings, which are based on the curves generated for cruise 17 for all combinations of taxonomic groups tested (all motile species). The best agreement with the rankings for all species occurs with all five groups tested (polychaetes, bivalves, gastropods, amphipods, and isopods); the next best is with polychaetes-and-bivalves tested. Polychaetes-and-amphipods were not compared because these are the two most difficult groups to identify and amphipods are most easily lost

Table 10. Station Rankings Based on Rarefaction Curves For Cruises 17 Through 20 and Shannon-Wiener Diversity Values (H')

Rank	Cruise 17		Cruise 18		Cruise 19		Cruise 20	
	Station	H'	Station	H'	Station	H'	Station	H'
1	D3	3.184	H9	2.723	H14	2.666	H14	3.698
2	C11	3.160	H8	2.327	C11	1.968	H8	2.509
3	H9	2.357	C11	3.248	C6	2.612	H9	2.679
4	H8	2.284	C6	2.031	H8	2.944	M9	2.787
5	H14	2.373	H12	1.647	M9	2.862	M6	2.669
6	M8	2.403	S10	2.169	M6	2.952	C11	1.938
7	M9	2.319	M8	2.933	M8	3.015	S10	2.548
8	M6	2.430	M6	2.169	S10	2.274	M8	2.316
9	M7	2.746	M7	1.896	M7	2.932	C6	2.169
10	H12	1.857			H12	2.209	M7	2.567
11	S10	1.770						
12	H1	0.752						

Table 11. Ranking of Stations, Based on Rarefaction Curves Generated From Cruise-17 Data

Rank	All Species	Bivalves Polychaetes Amphipods Isopods & Gastropods	Bivalves & Polychaetes	Bivalves & Gastropods	Bivalves	Polychaetes	Gastropods	Isopods & Amphipods	Isopods	Amphipods
1	D3	D3	C11	H9	M8	C11	H9	D3	H8	D3
2	C11	C11	D3	D3	C11	D3	D3,H14,H8*	C11	M8	C11
3	H9	H9	M8	C11	M9,D3,M6*	M8	C11	H8	C11,M6,M9*	H14
4	H8	M8	H9	M8,H14*	M7,H9*	H9	H12	M6	D3,S10*	M6,H9*
5	H14	H8	M7,M9*	H8	H14	M7	M8	H14	H12,H9,M7*	H8
6	M8	H14	M6	M9	H8	M9,H8*	M9,S10,M7*	H9,M9*		M9
7	M9	M9	H8	M7,H12,M6*	S10	M6	M6	M8		M8,M7,S10*
8	M6	M6	H14	S10	H12	H12,H14*		S10		H12
9	M7	M7	S10	H1	H1	S10		M7		H1
10	H12	H12	H12					H12		
11	S10	S10	H1					H1		
12	H1	H1								

* Curves for these stations had equal maximum values.

during remote sampling of soft substrates. The results for the other three cruises in which rarefaction curve comparisons between taxonomic groups were generated were essentially identical in that the agreement between the rankings of curves when all species were used versus curves of some of the taxonomic groups changed in a similar way.

Cluster analyses and selection of indicator species

Station comparisons. Cluster analyses to compare species assemblages from different stations gave four general clusters that could have been predicted from the substrate composition of the stations. The hard substrate stations were consistently correlated in each monthly analysis. The cobble stations aggregated as did Stations M6, M7, and M8. M9 and S10 were more closely correlated to each other than to any of the three other soft substrate stations. The clay content of the substrate at M9 was much more similar to that of S10 than to that of the other M stations, as was the depth of the substrate. S10 did show affinities to the cobble stations, particularly C6.

Two procedures were used to identify species or species groups to be studied as indicators of change. The major criteria for selecting species were that a species be (1) specific to substrate type; and (2) numerous enough to study. The first method was to determine correlation coefficients and run cluster analyses on all motile species that had been found in numbers of $30/m^2$ at least once at some station. The cluster analyses based on correlation coefficients were unmanageable because of the number of species (68) and the variation from month to month. Members of obvious groupings one month that correlated to a substrate type were grouped with other species the next month.

It was important to select species that were consistently correlated. Therefore, all species pairings that did not have a correlation coefficient value of 0.5000 or better (>0.01 significance) for at least 2 months were rejected. Table 12 lists the species that were consistently correlated to at least one other species. The amphipod *Metopella angusta* (Code No. 46) and the bivalve *Thracia myopsis* (Code No. 37) are examples of species that are associated with a number of species consistent for distinct substrate types. *Metopella* is found in the hard substrate communities and *Thracia* is found in good densities in the mud stations though not at S10 or M9. Probably because M9 had affinities to the other mud stations and S10 had affinities to the cobble substrate communities, no distinct species groupings could be identified for the sand stations.

The second method for selecting indicator species involved only those species that had occurred at only one station for all trips. Species that were collected at more than one substrate type were also screened out. As Table C1 shows, this eliminated almost all species. Therefore, a compromise was used to obtain the list of species in Table 13; included are all species that were associated with a particular substrate in numbers greater than $10/m^2$ (possibly associated with more than one station), but never associated with other substrate types in numbers above $10/m^2$. These species might be selected for closer study. It is interesting that *Metopella angusta*, which correlated for hard substrate fauna, does not appear on Table 12 because it was found in numbers greater than $10/m^2$ at one cobble station at least, and was found at virtually all stations (Table C1). *Thracia myopsis* would be a good indicator species for the three mud stations (M6, M7, M8), but not for the sand stations.

The data in Tables 6, C3, C4, and C5 show a consistent pattern of variation in distribution and density of species even within a single measurable segment of a seemingly homogeneous substrate. Indicator species, if itis possible to use them, will most likely have to be selected for each station and not from general substrate types.

Discussion

The most important result of the benthos study was the documentation of the natural variability in the system. The variation from month to month at each station was the most consistent finding. From month to month there was up to a factor of 2 variation in the number of species at a station. In fact, the species numerically dominant one month were frequently absent the next month.

The species tend to change with the substrate type, but correlations are not statisically significant. This is a heterogeneous environment and only a minority of the species appeared to require a particular substrate. Indicator species, if it is possible to use them, will most likely have to be selected for each station and not from general substrate types.

Table 12. Results of Correlation Analyses for Species Assemblages to Determine Indicator Species for Future Studies

Code No.	Species	Correlated Species (by code number) 2 out of 2	3 out of 3	4 out of 4	3 out of 4
2	Phyllodoce mucosa				6,16,18
3	Exogone dispar			14	
4	Neries pelagica				22,23
5	Nephtys ciliata				14,23,29
6	Glycera capitata				2
8	Ninoe nigripes				17
9	Aricidea jeffreysii				19
10	Scoloplos fragilis				27
11	Naineris quadricuspida	65			14
12	Spio setosa				13
13	Travisia carnea				12,14
14	Notomastus luridus	65		3	5,11,13,15,18
15	Euclymene collaris	65			14
16	Maldane sarsi				2
17	Praxillella gracilis				8,36
18	Myriochele heeri				2,47
19	Owenia fusiformis			38	9,20
20	Pectinaria granulata			38	19,46,47,48,50,51
22	Spirorbis borealis	59,63			4,23,25,42
23	Spirorbis spirillum				4,5,22,42,45,46,48
24	Spirorbis violaceus	62			
25	Hydroides sp.				22,30,36,37,44,46,48,51
26	Nucula delphinodonta				27
27	Musculus niger				10,26,28
28	Modiolus modiolus				27
29	Crenella faba	65			41,46
30	Astarte undata			37	34,46
34	Mya arenaria				30,51
35	Hiatella spp.			42	
36	Periploma papyratium				17,25
37	Thracia myopsis			30	25,44,45,46,47,48,51,53
38	Leptocheirus pinguis			19,20	41
39	Unciola irrorata	65			5,49
41	Corophium crassicorne	65			29
42	Ischyroceras anguipes			35	22,23
43	Photis reinhardi	62			
44	Sympleustes glaber		56		25,45,48,51
45	Pontogeneia inermis		54,55,56	46	23,37,47,48
46	Metopella angusta	62	54,55,56		20,23,25,29,30,37,48,50
47	Caprella linearis	57,64			18,20,37,51
48	Caprella septentrionalis	60	54,56	51	20,23,25,37,49
49	Ischnochiton alba				5,39
50	Tonicella rubra				20,46
51	Achelia spinosa		56		20,25,34,37,44,48 53
52	Chirodotea tuftsi			53	
53	Edotea montosa			52	37,51
54	Balanus balanoides		48,55		45,46
55	Eualus pusiolus		45,54		
56	Asterias sp.	60	45,46,48,51		
57	Ophiopholus aculeata		47		
58	Strongylocentrotus drobachiensis	60			
59	Moelleria costulata	63			
60	Margarites groenlandica	58	56		
62	Lacuna vincta	24,43			
63	Alvania areolata	22			
64	Alvania castanea	47			
65	Tharyx sp.	11,15,29,39,41			

*Table 13. Species Characteristic of Specific Substrate Types, Ranked According to the Total Number of Individuals per Square Meter**

Substrate Type:		Hard						Cobble					Mud					
Station Number:		H1	H8	H9	H12	H14		C6	T2	T3	C11		M6	M7	M8	M9	S10	
Rank	Species						Total Animals					Total Animals						Total Animals
1	Spirorbis violaceus		+	+	+	+	622.8											
2	Lacuna pallidula	+	+	o		o	454.9											
3	Eualus fabricii	+	+	+		+	208.5											
4	Tonicella marmorea	o	+	+	+	+	174.9											
5	Maldanopsis elongata		+	+	+	+	144.8											
6	Idotea phosphorea	+	o				96.4											
7	Amphitrite cirrata		+	+	o	+	89.7											
8	Janira alta			+		o	54.0											
9	Polycera lessonii	+					56.1											
10	Proboloides holmesi		+	o			42.3											
11	Mitrella rosacea			+		+	36.8											
12	Nicolea venustula				+		25.6											
13	Potamilla reniformis		o	+		o	16.1											
14	Colus stimpsoni					+	14.7											
15	Aequipecten irradians		o			+	13.4											
16	Mitrella dissimilis			+			13.3											
1	Asterias rubens	+	+	+			338.7			o		2.5						
1	Lacuna vincta		+	+	+	+	1237.4						o		o			1.5
2	Anomia aculeata	o	+	+	+	+	394.3								o			2.5
3	Velutina laevigata	+	+	+	+	+	103.1								o		o	1.6
4	Nymphon grossipes	o	+	o	o	o	101.0						o					0.7
5	Acmaea testudinalis	+	+	o	+	+	83.4						o		o			5.0
6	Clymenella torquata		o	+		+	34.6										o	2.5
1	Tonicella rubra	+	+	+	+	+	2081.3				o	3.3	o					2.5
2	Alvania castanea	o	+	+	+	+	657.4	o			o	5.0	o					0.7
3	Dodecaceria concharum	+	+	+	+	+	355.4				o	2.5	o					0.7
4	Musculus discors		o	+		+	208.1	o			o	5.8		o	o			2.5
5	Cirratulus cirratus		+	+	+	+	105.2				o	3.3	o					0.7
6	Flabelligera affinis		+	+	o	+	65.5	o			o	5.0				o		0.8
7	Corophium boneili		+	+		o	49.6				o	5.0					o	0.8
1	Lunatia immaculata							+			+	46.4						
2	Polycirrus eximius										+	12.5						
3	Odontosyllis fulgurans										+	10.5						
1	Syrrhoe crenulata			o			2.7	+		+	o	55.0						
2	Monoculodes tuberculatus		o				5.3	o		+	+	40.0						
3	Lumbrineris tenuis				o		3.2	o			+	37.5						
1	Scolelepides viridis										+	27.5					o	0.8
2	Lora pleurotumania										+	20.5	o		o	o	o	5.5
1	Erichthonius rubricornis					o	2.7	+		+	o	42.5					o	0.8
2	Phoxichildium femoratum		o				2.7	+			+	33.3			o			1.4
3	Anonyx sarsi		o				2.7	o			+	15.0					o	1.7
4	Lora turricula		o				2.7				+	10.0					+	2.7
1	Maldane sarsi												+	o	+	o		1844.5
2	Thracia myopsis												+	+	+	o		326.5
3	Chiridotea tuftsi												o	+			+	194.1
4	Tellina agilis													o		+	+	147.3
5	Cyathura polita												+		o			49.1
6	Anachis haliaecti												+	o				25.9
7	Hippomedon propinquus												+	o	o		o	20.8
8	Apistobranchus tullbergi												+	o	o			19.5
9	Eudorella trunculata													+	+			16.7
1	Sternaspis scutata	o					2.3						+	o	o		o	1238.6
2	Artica islandica		o				2.7						+	+	+	+	o	310.0
3	Axinopsis orbiculatus					o	5.3						+	+	+	+		165.8
4	Edotea triloba		o			o	5.4						+	+		o		35.7
5	Ptilanthura tenuis		o				5.3						+		+			31.2
6	Chaetoderma nitidulum				o		4.0						o		+			27.5
1	Spiophanes bombyx										o	3.3				+	+	314.9
2	Nephtys picta							o				5.0	o			+	+	90.9
3	Halcampa duodecimcirrata										o	2.5				+		40.8
4	Praxillura ornata										o	3.3			+			11.7
1	Lampros quadriplica					o	2.3				o	2.5		o		+	+	100.2

* Data from all cruises and all stations were used.

Note: + indicates 10 or more animals per station.
o indicates less than 10 animals per station.

In a future study of offshore sand and gravel mining, benthic community studies should utilize permanent stations, as was done in NOMES, but the sampling scheme should be altered. A limited number (two to four) of stations should be sampled intensively on a quarterly schedule. Fifteen to twenty replicate samples should be taken at each station every 3 months and analyzed separately so that aggregated distributions can be identified. Instead of the diversity indices used by benthic biologists, a list ranking species by some system that incorporates both numbers and biomass per unit area would seem to be a more useful way of describing and comparing communities. This would provide a more realistic picture of community organization and dynamics than monthly sampling with fewer replicates. During the sampling period, the region surrounding the mining area should be surveyed to determine the distribution of substrate types and to characterize the dominant components of their communities.

4.1.2 Phytoplankton

Although numerous phytoplankton studies have been conducted in the Gulf of Maine (fig. 10), starting with Bigelow (1913), the immediate area of the NOMES site had received very little detailed study prior to 1971. The NOMES investigations included both the test site and a coastal transect to the north.

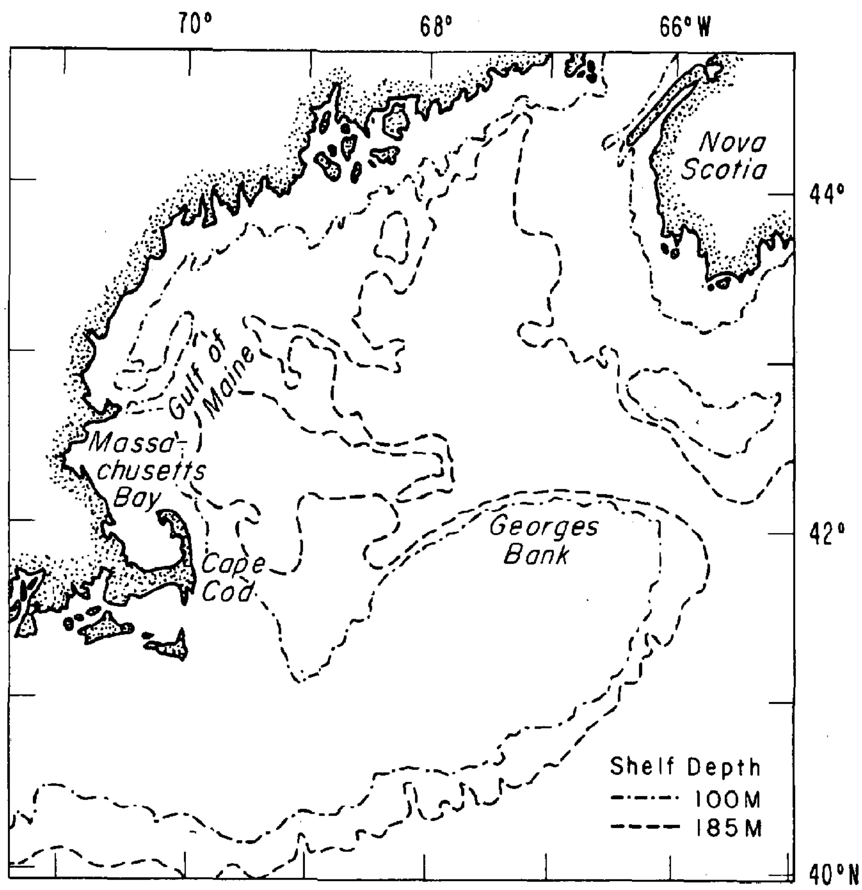


Figure 10. Northeastern coastal zone, including the Gulf of Maine and Massachusetts Bay.

Coastal transect

The coastal study, begun in the summer of 1971, was conducted to examine the variability of phytoplankton along a 80-km transect from Boston Harbor to Rye, New Hampshire. Data were collected monthly, from August 1971 to August 1972, at six stations located 2 to 5 km offshore (fig. 11): Rye, Newburyport (off the Merrimack River), Annisquam, Bakers Island, Flip Rock, and Pope Rock.

Chlorophyll-a concentrations were determined at all six stations, at five depth intervals. Highest values occurred in the spring and fall, as expected from phytoplankton blooms, running about 10 to 12 mg/m^3. Low values in the summer and winter were about 2 mg/m^3.

Phytoplankton were identified and counted in terms of cell numbers per milliliter. All six stations were under the influence of river runoff as

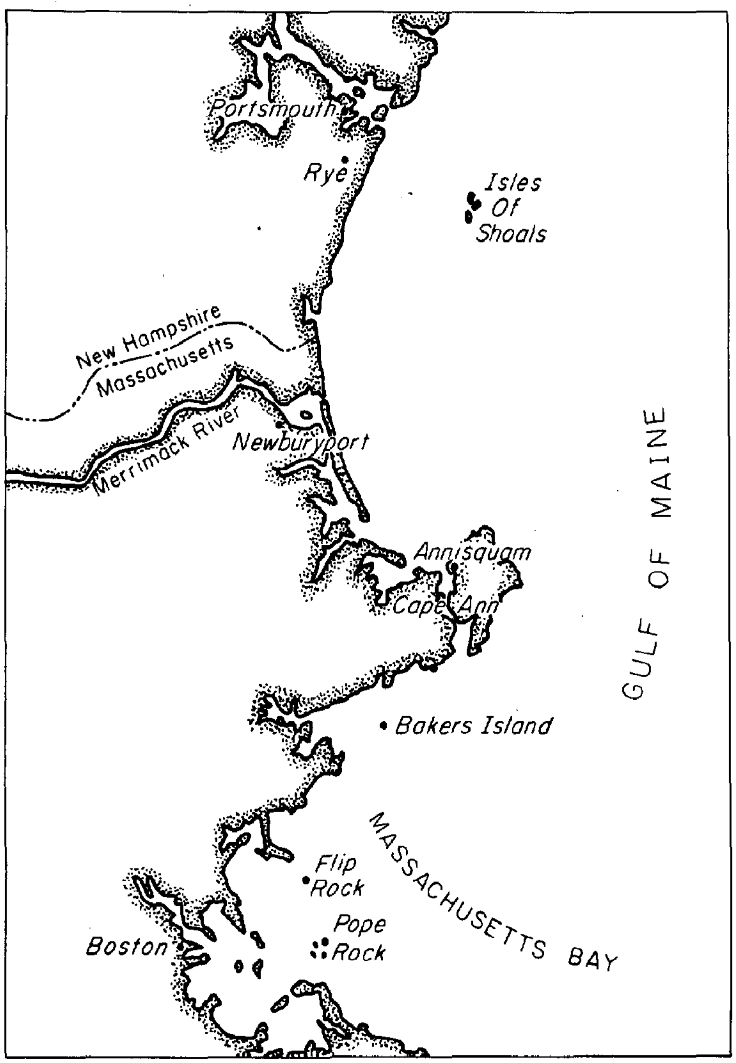


Figure 11. Coastal transect from Rye, N.H., to Boston, Mass.

well as currents, which makes comparison between and among stations difficult. The stations to the north of Cape Ann were slightly colder and had higher transparencies than those to the south.

Table 14 shows the maximum population of each species encountered at a given date; Table 15 shows frequency and abundance of species over the entire sampling period. In late June 1972 the species *Skeletonema costatum* constituted 92% of the phytoplankton to Annisquam (2009 cells per milliliter at the surface), which is the area where the 1972 "New England Red Tide" developed (Mulligan, 1973, 1975). Seasonal cycles were somewhat more advanced at the southern stations.

In general, more species were identified in the three northern stations (>50 at Rye) than in the three stations south of Cape Ann (frequently <10), which may correlate in part to the greater influence of river discharge to the north. With the exception of the bloom of *Gonyaulat tamarensis* at the northern stations, the major organisms at all stations were the same.

Massachusetts Bay

Following the selection of the site of the experimental mining operation in the fall of 1972, a variety of sampling programs was considered by the NOMES Technical Advisory Committee to characterize accurately the phytoplankton and associated hydrographic conditions in Massachusetts Bay. Sampling schemes ranged from sampling at one location over entire tidal cycles to the establishment of a grid of permanent sampling stations.

Table 14. The Most Abundant Species Recorded From Rye to Pope Rock, 1971-72

Species	Maximum Cells/mℓ Observed	Date Observed	Station
Skeletonema costatum	2164.5	6-8-72	Pope Rock
Chlamydomonas sp.	1551.7	12-16-71	Flip Rock
Chaetoceros debilis	663.8	4-20-72	Annisquam
Chaetoceros compressus	265.0	4-20-72	Annisquam
Thalassiosira nordenskioeldii	251.0	4-20-72	Pope Rock
Phaeocystis pouchetii	244.6	7-12-72	Merrimack
Thalassionema nitzschioides	242.1	11-18-71	Annisquam
Leptocylindrus danicus	229.3	10-21-71	Flip Rock
Eutripea sp.	169.2	7-12-72	Flip Rock
Nitzschia seriata	158.0	9-23-71	Bakers Island
Leptocylindrus minimus	140.1	10-21-71	Annisquam
Carteria sp.	135.0	6-8-72	Bakers Island
Rhizosolenia delicatula	99.4	10-21-71	Flip Rock
Thalassiosira sp. 1	84.1	8-23-71	Pope Rock
Fragilaria sp.	68.8	3-9-72	Merrimack
Detonula confervacea	65.0	4-20-72	Pope Rock
Chaetoceros didymus	49.7	6-8-72	Merrimack

Table 15. Comparison of the Frequency of Occurrence and the Abundance of Species Recorded From Rye to Pope Rock 1971-72

Species	Frequency-of-Occurrence Ratio	Abundance Scale*
Thalassionema nitzschioides	.67	9
Nitzschia closterium	.44	31
Cocconeis scutellum	.32	48
Skeletonema costatum	.32	1
Leptocylindrus danicus	.24	10
Thalassiosira sp. 1	.24	28
Navicula sp. 2	.22	37
Chlamydomonas sp.	.22	29
Navicula sp. 9	.18	42
Chaetoceros compressus	.17	6
Navicula sp. 1	.17	38
Licmophora abbreviata	.15	47
Distephanus speculum	.15	41
Eutripea sp.	.15	11
Thalassiosira sp. 2 (r+2.5)	.14	27

* Scale derived by comparing maximum populations of each species over the entire sampling period where the number 1 is the most abundant on a scale from 1 to 55.

After all sampling proposals were evaluated, 16 stations were established in a 13 x 13 km grid (fig. 12). Coordinates of the corners of the grid follow.

A1	42°22'50" N.	A4	42°22'50" N.
	70°51'50" W.		70°43'50" W.
D1	42°17'10" N.	D4	42°17'10" N.
	70°51'50" W.		70°43'50" W.

Station D1 was eliminated from the sampling schedule because of insufficient depth and shifting sand bars. Also, an additional station sampled on some dates was located between B2 and B3 in the center of the proposed mine site.

From December 1972 to May 1973 biweekly samples were obtained at all stations. From June to December 1973, five "primary" stations (A2, A4, B3, C2, C4) were sampled biweekly, and the remaining stations were sampled once a month. One trip per month was made in winter when productivity was low.

To assist in interpreting phytoplankton data with respect to water mass movements and water chemistry, hydrographic and physical-chemical measurements

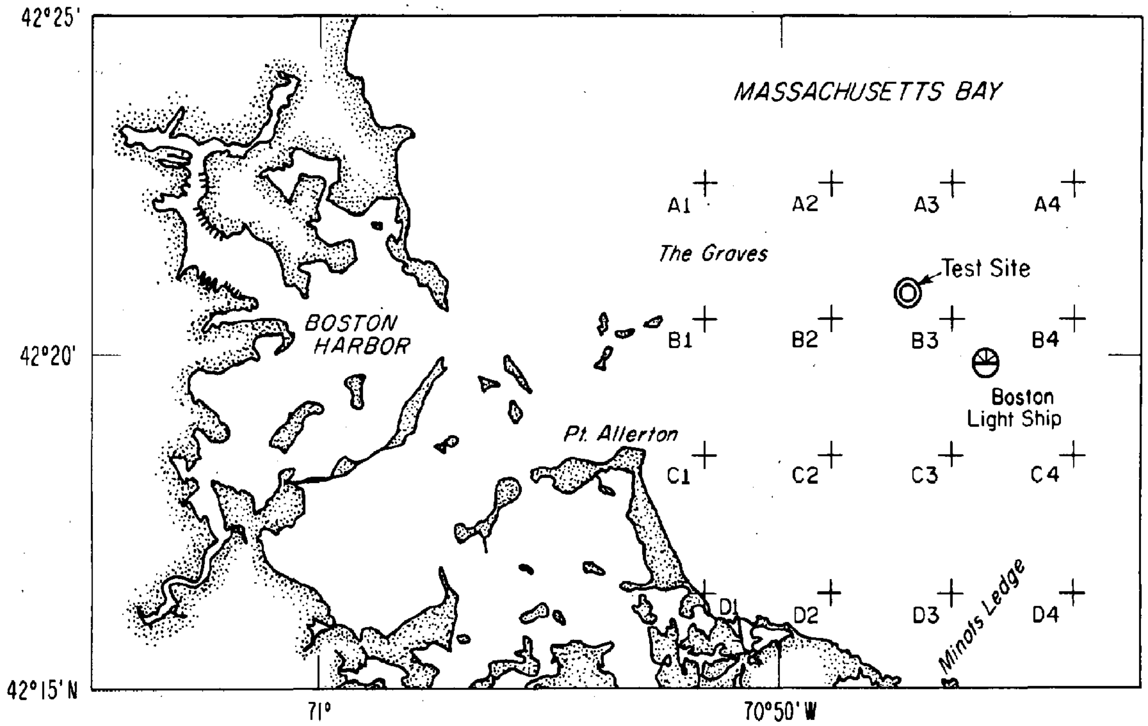


Figure 12. Massachusetts Bay and NOMES station locations.

were made in conjunction with the collection of water samples for plankton analyses. These data include vertical profiles for each station of salinity, temperature, and light transmittance and are reported in Sec. 4.4, "Physical Oceanography." Also, chemical analyses of water samples collected during the spring of 1973 are reported in Sec. 4.3, "Chemical Oceanography."

Chlorophyll-*a*. Chlorophyll-*a* concentration measurements (measures of photoplankton abundance) were integrated over depth; the values for the five primary stations are shown in figure 13. These data show bimodal spring and fall blooms. Chlorophyl-*a* values ranged between about 10 mg/m^2 in the winter to about 250 mg/m^2 during the spring bloom. Phytoplankton populations were larger closer to shore, probably as a result of nutrients contributed by sewage discharges and fresh-water runoff and from the resuspension of bottom sediments and nutrients in shallow, nearshore waters.

Biomass. Biomass provides a more accurate description of phytoplankton variation than cell counts because marine phytoplankton vary greatly in cell size. Biomass was evaluated at the five primary stations on each of the sampling dates. At other stations, biomass was evaluated periodically.

Biomass concentrations among four primary stations, when integrated over depth, ranged from 27-6600 mg C/m^2 during 1973. (Station C4 appeared anomalous and will be discussed separately.) As expected, the maximum concentrations were observed during spring and fall bloom periods. Minimum concentrations occurred immediately after the spring bloom and during the winter months. The annual cycle of biomass at station B3, near the mine site, indicated a strong seasonal periodicity of phytoplankton production (fig. 14).

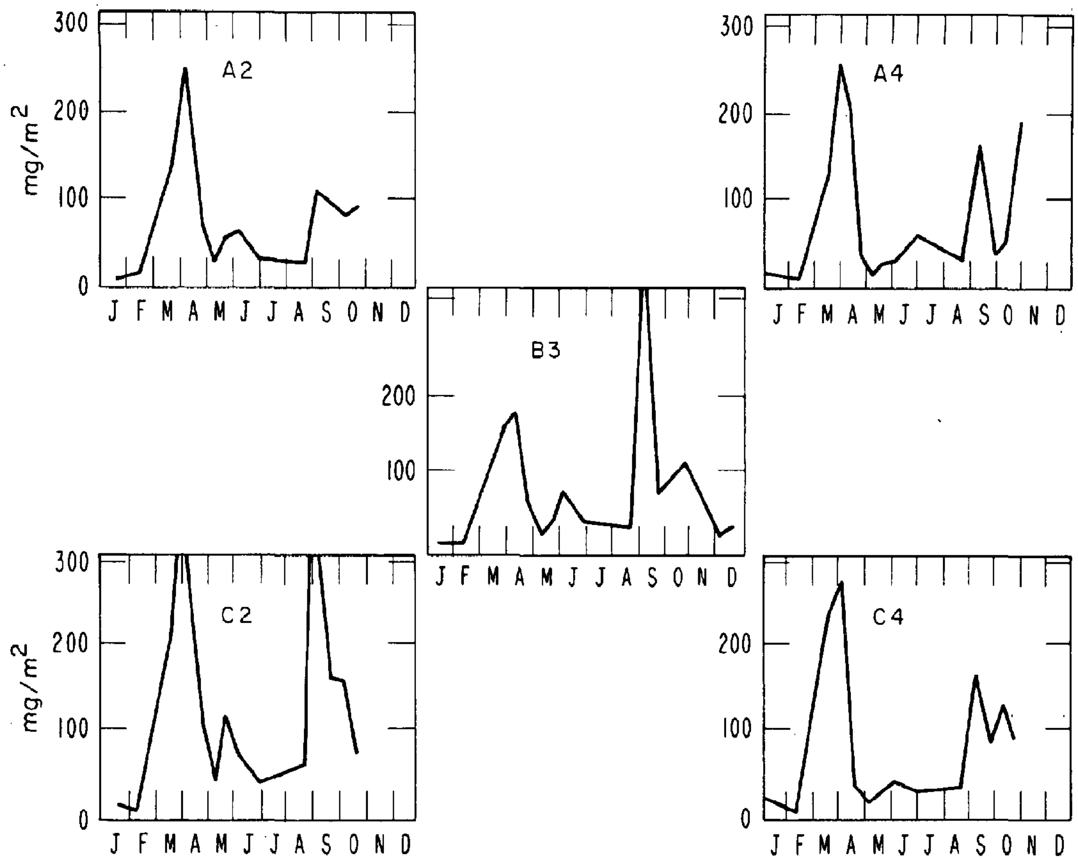


*Figure 13. Chlorophyll-*a *values (mg/m²) recorded biweekly at the five primary stations in 1973.*

Spring bloom biomass concentrations ranged from 4700-6600 mg C/m^2. The 1973 spring bloom lasted approximately one month (mid-March through mid-April), the maximum occurring simultaneously at all stations on March 31. Maximum annual biomass concentration was observed at this time and corresponded with maxima of chlorophyll-*a* and primary production.

Immediately following the spring bloom, biomass concentrations declined rapidly and by May 5 concentrations were below 500 mg C/m^2 at all stations. Following this decline, a secondary increase in biomass was observed (May 18) indicative of the biomodal spring phytoplankton bloom described previously. However, biomass concentrations during this secondary peak were much lower than the March peak and ranged from 305-2030 mg C/m^2. Concentrations at station C4 did not parallel those at the other primary stations. At station C4 the bimodal spring peaks were equivalent and maximum biomass observed was 4900 mg C/m^2.

The summer biomass concentrations remained generally low. In June, phytoplankton biomass again declined and ranged between 120 and 610 mg C/m^2. During July, phytoplankton populations increased slightly and ranged from

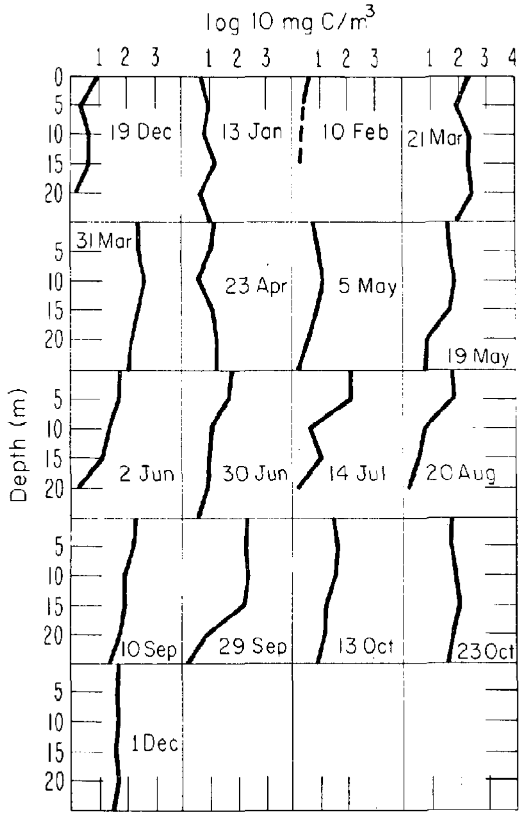


Figure 14. Vertical distribution of phytoplankton biomass at Station B3 from December 1972 to December 1973.

540-2400 mg C/m^2. August values were reduced to less than 1 mg C/m^2. These summer trends corresponded with chlorophyll-*a* and primary production.

As fall approached, phytoplankton populations increased at most stations and by mid- to late September a fall bloom was observed. The fall bloom was more variable in concentration and timing than the spring bloom. Concentrations among the inshore stations increased to more than 2500 mg C/m^2. At the offshore stations, A4 and C4, the fall bloom was less intense, and maximum observed values were approximately 1000 mg C/m^2. At both offshore grid stations the fall bloom appeared to have been delayed and was not observed until October.

Following the fall bloom, phytoplankton populations declined slowly through the early winter months. Samples taken at station B3 in December indicated a slight phytoplankton increase. However, this was rapidly attenuated, and typically low winter values were reestablished.

Annual variation in biomass among the Massachusetts Bay stations was similar. The seasonal periodicity observed with a large spring and smaller fall bloom of phytoplankton, followed by periods of lower phytoplankton growth in the summer and winter, is typical of north temperate waters, including the Gulf of Maine.

<u>Species composition</u>. The dominant phytoplankton species encountered and their periods of abundance are shown in Table 16. Phytoplankton population estimates are provided in terms of numbers, volume, and biomass.

Table 16. Dominant Phytoplankton Collected in Massachusetts Bay From 12-19-72 to 12-22-73

Bacillariophyceae	Vol./Cell (μ^3)	Carbon/Cell (picograms)	Dates of Occurrence	Period of Max. Abundance: Date of maximum abundance	No. Cells/ml at maximum abundance	Total vol. at peak (μ^3x10^5)	Total pg C at peak (x10^4)
Chaetoceros debilis	929.	78.	3/21-4/23, 5/19-6/2	6/2/73	910.	8.5	7.1
C. decipiens	4,500.	304.	3/21-4/17	4/17/73	196.	8.8	1.6
C. didymus	884.	82.	10/13	10/13/73	32.	0.28	0.26
C. socialis	200.	27.	2/10, 3/21-4/23, 5/19-6/2	4/12/73	3,400.	6.8	9.2
C. subsecundus	12,000.	717.	3/31	3/31/73	50.	6.	3.6
Coscinodiscus sp. 1	250.	34.	10/28-12/22	12/1/73	48.	0.12	0.16
Cylindrotheca closterium	1,200.	112.	1/13, 2/10-3/21, 9/10-9/30		206.	2.5	2.3
Detonula confervacea	545.	57.	3/21-3/31	3/31/73	2,900.	16.	1.7
Guinardia flaccida	58,000.	1,988.	12/1-12/22	12/22/73	50.	29.	9.9
Leptocylindrus danicus	880.	99.	7/14-10/28	9/10/73	4,900.	43.	49.
L. minimus	180.	25.	10/28-12/1	10/28/73	39.	0.07	0.10
Nitzschia delicatissima	340.	43.	9/30-10/28	10/13/73	280.	0.95	1.2
Porosira glacialis	44,000.	1,572.	3/21-3/31	3/21/73	140.	62.	22.
Rhizosolenia delicatula	1,000.	103.	10/28-12/1	10/28/73	1,200.	12.	12.
R. faeroense	18,000.	937.	3/21-3/31	3/31/73	33.	5.9	3.1
R. fragilissima	1,500.	129.	7/14-8/20, 9/30-10/28	7/14/73	970.	15.	13.
Skeletonema costatum	480.	52.	12/19, 2/10-3/31, 5/19-6/2, 7/14-12/1	10/13/73	3,300.	16.	17.
Thalassionema nitzschioides	720.	76.	12/19, 2/24-3/31, 4/17	3/31/73	100.	0.72	0.76
Thalassiosira decipiens	3,000.	242.	2/10, 3/21-3/31	2/10/73	38.	1.1	0.92
T. gravida	2,800.	218.	3/21-4/13	3/31/73	426.	12.	9.3
T. nordenskioldii	3,900.	260.	3/21-4/17	3/13/73	700.	27.	18.
T. species 1	3,600.	244.	12/19-1/13, 3/21-4/23	4/23/73	160.	5.8	3.9
T. species 2 (small)	59.	9.	5/19-7/14, 10/28	5/19/73	190.	0.11	0.17
Dinophycease							
Amphidinium crassum	1,300.	119.	5/5, 6/30-7/14	5/5/73	170.	2.2	2.0
Peridinium triquetrum	1,500.	113.	5/19, 6/30-10/30	8/20/73	103.	1.5	1.2
Chlorophyceae							
Unknown 1 (Chlamydamonas?)	280.	37.	12/19, 3/21-3/31, 5/5-7/14, 9/10	6/30/73	900.	2.5	3.3
Euglenophyceae							
Euglena	820.	84.	3/21-9/10	3/21, 3/31, 6/2	48.	3.9	0.4
Chrysophyceae							
Syracosphaera	2,600.	202.	10/13	10/13/73	41.	1.1	0.83
Unknown 2 (Phaecystis)	7.	2.	3/21	3/21/73	383.	2.7	7.7
Unknown 3 (Etripea?)	240.	33.	3/21-3/31, 4/23-6/30, 8/20, 9/30-10/28	5/5/73	43.	0.1	0.14
Unknown 4	15.	4.	12/19/72 12/1/73	12/19/72	870.	0.13	0.35

Resting spores. Resting spores (vegetative cells that can survive adverse conditions) were observed for eight species of phytoplankton collected in Massachusetts Bay (Table 17). Six of these are spring bloom organisms: *Detanula confervacea, Thalassiosira nordenskioeldii, T. gravida, Chaetoceros socialis, C. debilis,* and *C. subsecundus*. The remaining two are fall organisms: *Leptocylindrus danicus* and *Chaetoceros didymus*. Neither *Chaetoceros subsecundus* nor *C. didymus* was present in numbers sufficient for conclusions to be drawn from their appearance and subsequent spore formation. The remaining six, however, seem to fall into a pattern of a healthy cell "bloom" followed by distinctive spore formation.

Table 17. Phytoplankton Resting Spores Collected in Massachusetts Bay in 1973

Phytoplankton	Dates of Occurrence	Date of Maximum Occurrence	Maximum Occurrence Station	Depth	No. Cells at Maximum/ℓ	Trend of Development
Chaetoceros debilis	4/23 5/19-6/2	4/23	DS	50 m	82,000	offshore → inshore
C. didymus	9/30-10/13	9/30	A2	10 m	14,000	
C. socialis	4/13-4/23 5/19-6/2	4/17	DS	10 m	340,000	offshore → inshore
C. subsecundus	3/31	3/31	B3	surf	50,000	
Detonula confervacea	3/21-4/13	3/21	B4	20 m	900,000	offshore → inshore
Leptocylindrus danicus	9/10-10/28	9/30; 10/28	A2 C4	15 m 15 m	7,500	offshore → inshore(?)
Thalassiosira gravida	3/31-4/13	3/31	C4	5 m	24,000	offshore → inshore
T. nordenskioeldii	3/31-4/17	4/13	A2	15 m	211,000	inshore → offshore(?)

Productivity. Net marine phytoplankton primary productivity varies from an average of 200 mg C/m^2/day in oligotrophic habitats such as the Sargasso Sea (Menzel and Rhyther, 1960) up to 3350 mg C/m^2/day in nutrient-rich upwelling areas off the southwest African coast (Lloyd, 1971). Habitats on the east coast of North America vary considerably with regard to primary productivity levels. The shallow portion of the Gulf of Maine has a high annual fish yield probably supported by the highly productive phytoplankton community.

Primary productivity at station B3 was measured in situ during 1973 and 1974, and estimates of whole-day carbon fixation were calculated (Table 18). The data provided a clear picture of the annual cycle of primary productivity for Massachusetts Bay stations (fig. 15). A maximum primary productivity valued at 1900 mg C/m^2/day was recorded in Massachusetts Bay in 1973.

Annual primary productivity was 230 g C/m^2/yr, determined by integrating daily values over time for the year. This value was obtained from in-situ

Table 18. In-Situ Vertical Primary Production Profile (mg $C/m^3/hr$), and Integrated Hourly and Daily Rates at Station B3 From March 1973 to June 1974

Depth (m)	3/21/73	3/31/73	4/13/73	4/23/73	5/5/73	5/19/73	6/30/73
Surface	17.78	41.88	12.56	0.61	2.87	7.55	3.40
1	22.60	41.00	16.00	1.18	3.26	9.40	18.20
3	25.80	17.80	22.76	1.06	2.99	10.70	11.00
5	23.77	9.60	15.50	1.90	2.85	9.10	4.86
8	7.36	2.88	2.40	2.37	2.54	9.80	1.90
10	0.00	1.79	1.98	2.27	2.30	5.50	0.95
12	0.00	0.60	0.96	2.15	1.40	3.60	0.77
15	0.00	0.59	0.54	2.38	0.85	2.30	0.14
20	0.00	0.42	0.07	1.35	0.22	0.70	0.00
25	0.00	0.32	0.00	0.76	0.10	0.16	0.00
mg $C/m^2/hr$	172	160	129.4	43	38.6	119.6	72.3
mg $C/m^2/day$	1383	1170	1202	332	284	963	881

Depth (m)	7/14/73	8/20/73	9/10/73	9/29/73	10/13/73	10/28/73	12/1/73	12/22/73
Surface	10.39	3.67	12.96	2.31	8.90	16.01	2.50	3.27
1	11.53	3.96	19.58	2.81	10.00	17.33	5.29	2.81
3	11.65	6.13	15.12	4.34	11.26	12.35	3.97	6.09
5	9.22	4.03	9.30	3.36	8.82	6.68	3.32	5.57
8	2.07	3.24	2.89	1.24	4.70	2.85	2.08	4.32
10	1.74	3.12	1.15	0.97	2.98	0.67	1.91	3.03
12	1.10	2.48	0.41	0.73	1.92	0.54	0.90	2.67
15	0.72	2.06	0.32	0.24	1.04	2.40	0.80	1.58
20	0.18	1.89	0.28	0.00	0.48	0.81	0.35	0.55
25	0.00	1.70	0.00	0.00	0.20	0.00	0.21	0.00
mg $C/m^2/hr$	85.6	71	101.9	30.3	93.6	98.9	42.2	64.4
mg $C/m^2/day$	757	607	839	240	615	672	337	382

Table 18. (Continued)

Depth (m)	1/26/74	2/16/74	3/2/74	3/16/74	4/6/74	4/20/74	5/5/74	5/18/74	6/1/74
Surface	0.56	1.66	23.63	24.96	11.49	1.85	4.82	9.45	14.70
1	1.13	2.05	22.41	30.39	11.03	2.07	3.63	7.41	10.48
3	1.64	1.91	21.79	16.77	7.93	3.26	3.45	9.83	6.65
5	2.18	2.19	12.75	9.36	4.94	3.05	3.59	11.24	3.07
8	1.21	2.29	5.54	1.82	2.35	3.01	2.47	8.24	1.98
10	1.40	2.57	3.06	1.92	1.72	2.38	2.26	5.20	0.15
12	0.68	1.77	0.34	4.16	1.05	2.00	2.46	3.75	1.02
15	0.72	0.51	0.20	3.36	0.46	0.76	1.83	0.87	0.26
20	0.40	0.37	0.00	4.10	0.27	0.54	0.32	0.05	0.00
25	0.47	0.31	0.00	3.34	0.14	0.85	0.04	0.00	0.00
mg C/m^2/hr	24.3	33.2	142.5	176.1	66.0	43.3	49.6	107.7	52.9
mg C/m^2/day	160	214	1555	1915	533	360	456	940	764

profiles at station B3. Station-to-station variation suggests that 200-350 g C/m^2/yr is a reasonable range for annual productivity at the Massachusetts Bay stations.

Annual net productivity values for neritic water along the east coast of the United States and Canada are presented in Table 19. Annual primary productivity for Massachusetts Bay corresponds with that of Georges Bank, which is nearest geographically to the sampling area. Massachusetts Bay is among the most productive regions listed.

An incubation tank, constructed for shipboard measurement of primary productivity, provided information on horizontal variability in carbon fixation among the five major Massachusetts Bay stations. Because only four depths were sampled per station these values are considered estimates of primary productivity. Simulated in-situ experiments were conducted from July 1973 to June 1974. The incubation tank values were corrected with the in-situ profile values by incubating duplicate samples, one in situ and one in

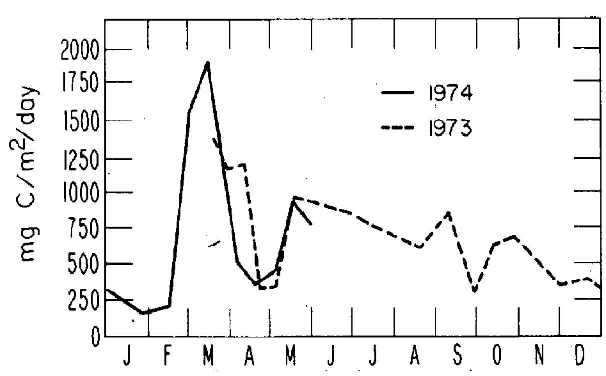


Figure 15. Daily primary production at Station B3, measured in situ from March 1973 to June 1974.

Table 19. Annual Estimates and Seasonal Maxima of Net Primary Productivity in Massachusetts Bay and Other Selected Marine Regions

Seasonal Maxima	g C/m^2/day
Massachusetts Bay (Parker, 1974)	1.3-1.9
Chaleur Bay, Can. (Legendrė, 1971)	1.0
N.W. African Coast (Lloyd, 1971)	1.12-3.35
Coastal off New York (Ryther and Yentsch, 1958)	1.0
Chesapeake Bay (Taylor, Roland, and Hughes, 1964)	1.5-3.5
40°-50° N. Pacific (Parsons and Anderson, 1970)	0.66
Georges Bank (Teal and Kanwisher, 1966)	1.6
Nantucket Sound (Teal and Kanwisher, 1966)	0.60
St. Margarets Bay, Can. (Platt, 1971)	2.0
Annual Estimates	**g C/m^2/yr**
Massachusetts Bay (Parker, 1974)	200-340
Coastal off New York (Ryther and Yentsch, 1958)	160
Continental Shelf off New York (Ryther and Yentsch, 1958)	100
Long Island Sound (Ryther and Yentsch, 1958)	380
Georges Bank (Teal and Kanwisher, 1966)	120-300
Nantucket Sound (Teal and Kanwisher, 1966)	150-200
St. Margarets Bay, Can. (Platt, 1971)	250-270
Western Central Atlantic (El-Sayed, 1972)	100
Sargasso Sea (Menzel and Ryther, 1960)	72

the tank. Percent difference in productivity was then used to correct all other tank-incubated samples.

Carbon fixation from the tank ranged from undetectable levels at the compensation depth (the depth where photosynthesis equals respiration) to 38.8 mg $C/m^3/hr$. Light inhibition was noted in the surface water samples, and maximum photosynthesis was measured at light levels corresponding to a depth of 1 m.

Primary productivity integrated to 1% I_0 (surface intensity) depth, ranged from 12 to 250 mg $C/m^2/hr$ (fig. 16). In general, an inverse relationship between distance to shore and primary productivity was noted. Values for an offshore control station, located 8 nmi east of the Massachusetts Bay stations, provided the lowest productivity estimates. The productivity graph is supplemented with values calculated from other NOMES stations (A1, A3, B2, B4, C1, C3). The productivity values for these stations were derived from assimilation indices (mg C/mg chlorophyll-*a*/m^2: Ryther and Yentsch, 1958; Flemer, 1970). Chlorophyll-*a* concentrations for each date were used to calculate primary productivity values in mg $C/m^2/hr$. These calculations provided a generalized view of the offshore trend of decreasing primary productivity.

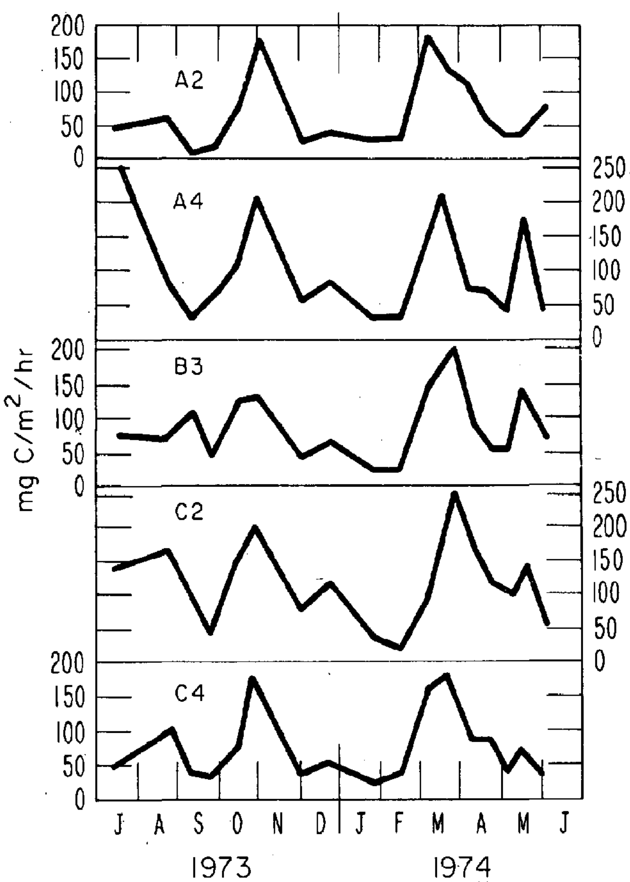


Figure 16. Daily primary production measured in on-deck incubation bath from July 1973 to June 1974.

Production at station C1 was inconsistently low. Depth at this station is 10 m at mean low water. Therefore, integration to 25 m could not be made at this station and comparison with deeper stations is not realistic.

In-situ profiles provided information on vertical variation-with-depth in the euphotic zone. Productivity was measured at 10 depths at station B3. Four-hour in-situ incubations were evaluated for rate of primary production, and values were converted to mg $C/m^3/hr$. Values ranged from undetectably low levels at the compensation point to 41 mg C/m^3 in the most productive portion of the euphotic zone. The euphotic zone was approximately 25 m deep, although it varied from 20 to 30 m. Surface productivity values were 80% of the 1-m values. It appears that light inhibition of photosynthesis accounts for this phenomenon (Marshall and Orr, 1928; Jenkins, 1937; Steeman-Nielsen, 1951). Maximum productivity took place at depths of 1-3 m where the range was 1-41 mg $C/m^3/hr$. Light intensity through this interval was 35-58% of the surface intensity (I_o), and maximum carbon fixation occurred at 58%.

Geographical variation in primary productivity among the Massachusetts Bay grid stations was evaluated by C-14 method at the primary stations and by chlorophyll concentration for all other stations. An estimate of annual primary productivity was calculated by combining the data from July 1973 to June 1974 at each station. Daily productivity values were calculated in the same manner as in-situ values. Carbon fixation as mg $C/m^2/day$ was integrated over sample dates during this 1-yr period and an annual production estimate was obtained. The values obtained in this manner correspond with those measured in situ at station B3. The estimate of annual phytoplankton carbon fixation by C-14 method was 230 mg $C/m^2/yr$.

Variations among the Massachusetts Bay grid stations show a trend of decreasing annual primary productivity with increased distance from shore. In addition, maximum production was observed on the southern side of the grid and a more gradual reduction toward the north was observed. The resultant distribution shows that inshore stations and those located in the southwestern area of the grid have the highest primary productivity. Offshore stations and those located toward the northeast showed lowest annual primary productivity. In general, productivity was reduced by approximately 40% along a transect from station C2 to station A4 (fig. 17).

Decreasing annual primary productivity in a seaward direction has been previously reported by Ryther and Yentsch (1958) and Mandelli et al. (1970) for the New York coastal region. Ryther and Yentsch suggested that the increased productivity was due to a more active nutrient regenerating mechanism in these shallow coastal waters, probably aided by storms and other mixing processes.

Addition of nutrients to coastal water appears to stimulate algal growth. Station C2 located near the proposed mine site shows highest chlorophyll-*a* concentration and primary productivity reported for the study area. The annual primary productivity estimate at this station was 340 mg $C/m^2/yr$, which suggests that this region is highly eutrophic. Because of the drainage pattern the northeastern and northern sections of the grid are least affected by harbor water and nutrient enrichment. These stations had lower chlorophyll-*a* concentrations, deeper euphotic zones, and lower primary productivity.

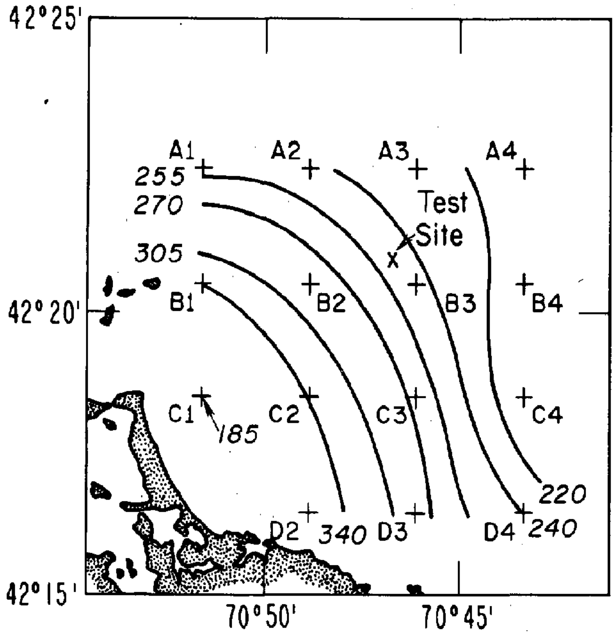


Figure 17. Isopleths of annual primary production (g C/m^2/yr) among the Massachusetts Bay stations.

In general, it appears that the ebbing tide carries a large volume of nutrient-rich water through narrow channels into the western margin of Massachusetts Bay. Progressive nutrient dilution with bay water distributes nutrients in decreasing concentrations seaward. Long shore currents and the Coriolis force deflect the water to the south. Primary productivity is also decreased in a seaward direction. However, in such a complex system many factors are likely to be responsible for the spatial variation in the biological parameters of the study area. The Merrimack River contributes more than 90% of the fresh water to Massachusetts Bay.

Discussion

Phytoplankton impacts from marine mining activities are classified as either site-specific or non-site-specific. Analyses of species composition, distribution, and abundance of phytoplankton populations in the Massachusetts Bay impact area revealed considerably more variability from station-to-station analyses than from diurnal analyses at a single station. These station-to-station analyses have allowed an interpretation of the phytoplankton developmental trends. For example, one can determine inshore-to-offshore trends in the seasonal development of phytoplankton populations.

The proposed NOMES Massachusetts Bay test site appears to be located at the center of a large gyre. It was also observed that the 16-station grid could be separated into two reasonably discrete regions by a line drawn through the center of the grid along a northeast to southwest axis, separating coastal phytoplankton populations from oceanic populations. Most of these trends would have been missed had the sampling proceeded at a single station over a 12-hr tidal cycle or along single transects drawn perpendicular to the shore. The grid design provided the best indication of plankton dynamics in this portion of Massachusetts Bay and is highly recommended for a future study of offshore sand and gravel mining.

4.1.3 Turbidity Experiments

During Project NOMES, it had been intended to make use of the unique aquarium complex at the University of California's Bodega Marine Laboratory in Bodega Bay, California (Davis and Nudi, 1971), in order to study the effects of suspended sedimentary particles on certain marine organisms. NOAA had funded the fabrication of most of the facility prior to Project NOMES, and it was hoped that studies of organisms analogous to those of Massachusetts Bay would reveal the reasonableness of extrapolating findings of such studies.

Following the termination of Project NOMES in 1973, the proposed research was redirected to include tests on estuarine organisms and was cofunded by NOAA and the San Francisco District of the U.S. Army Corps of Engineers. This work was reported elsewhere in detail (Peddicord et al., 1975). Therefore, only a brief summary is included here.

Experiments with varying levels of suspended sediment were conducted on both marine and estuarine organisms. The former were collected from Bodega Bay, and Bodega Harbor (about 100 km north of San Francisco Bay) furnished the estuarine organisms.

Twenty-four 84-ℓ aquariums were arranged either in three sets of eight or four sets of six to permit simultaneous replication. An open circuit permitted a once-through flow of particles and water, in the desired proportions, every 4 to 6 hr. Suspended sediment concentration, temperature, salinity, and dissolved oxygen were monitored and controlled; pH was monitored but not controlled.

Initial tests were conducted with suspended particles of kaolin, a "pure" clay; sensitive species were then exposed to bentonite, an "impure" clay more representative of San Francisco Bay sediments. Table 20 lists the test species.

Most exposure tests were conducted for 10 days, to simulate dredging operations in San Francisco Bay. Mortality was analyzed every 8 hr and LC50, 20, 10 estimates were made. From that information, time-concentration curves were developed (e.g., fig. 18).

The conclusions reached were as follows:

1) The lethal concentration of suspended bentonite was much lower for 2- to 3-cm-long bay mussels *Mytilus edulis* than for large mussels. Survival was reduced significantly by increasing suspended bentonite concentrations, with the effect exaggerated at summer temperatures. Survival was greater at saturated dissolved oxygen than at 5 ppm or 2 ppm, but little difference was apparent between the reduced levels. The short-term oxygen consumption of *M. edulis* in suspensions of bentonite was inversely correlated with concentration. The same experimental combinations of suspended bentonite, temperature, and dissolved oxygen, eventually causing death in *M. edulis*, also resulted in loss of byssal attachments, but after much shorter exposure times. Such loss may be an early and sensitive indicator of effective death.

Table 20. Bodega Marine Laboratory Test Species

Kaolin Tests		
Strongylocentrotus purpuratus	-	Sea Urchin
Crangon franciscorum	-	Bay Shrimp
Pagurus hirsutiusculus	-	Hermit Crab
Sphaeroma pentodon	-	Snail
Nassarius obsoletus		
Tapes japonica		
Molgula manhattensis	-	Tunicate
Styela montereyensis	-	Tunicate
Mytilus californianus	-	Mussel
Ascidia ceratodes	-	Marine tunicate
Crangon nigromaculata	-	Spot-tailed sand shrimp
Palaemon macrodactylus	-	Euryhaline shrimp
Cancer magister (5 cm)	-	(Commercial) crab

Kaolin & Bentonite Tests		
Mytilus edulis (2-5 cm & 10 cm)	-	Blue bay mussel
Crangon nigricauda (3-5 cm)	-	Sand shrimp
Anisogammarus confervicolus	-	Amphipod
Neanthes succinea	-	Polychaete
Parophrys vetulus	-	English sole
Cymatogaster aggretata (6-8 cm)	-	Shiner perch
Morone saxatilis	-	Striped bass (fingerlings)

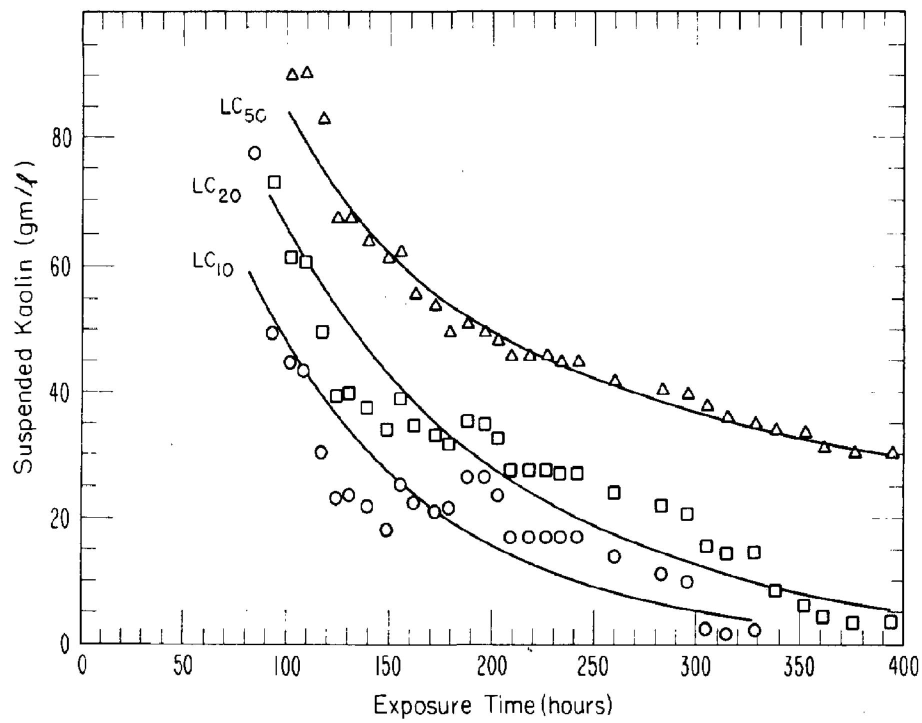


Figure 18. Time-concentration mortality curves for 6-8.5 cm sand shrimp Crangon nigromaculata *at 10°C and with saturated dissolved oxygen. Experiment was conducted with six suspended kaolin concentrations from 10 gm/ℓ to 100 gm/ℓ.*

Mussels that became detached and fell to the bottom would also be susceptible to covering by sedimentation, particularly near a dredging operation that created suspended solids high enough to cause detachment initially.

2) Under conditions of low temperature and saturated dissolved oxygen, survival of 3- to 5-cm sand shrimp *Crangon nigricauda* was high, even in high concentrations of suspended bentonite. Survival was reduced by summer temperature, even at saturated oxygen levels. Decrease in dissolved oxygen from saturation to 5 ppm dramatically reduced the tolerance to suspended bentonite.

3) Fingerling striped bass *Morone saxatilis* were killed at lower suspended bentonite concentrations than were any of the invertebrates tested. Survival varied inversely with suspended bentonite concentration and directly with dissolved oxygen and temperature. These factors were shown to interact in a complex, nonadditive manner to reduce survival.

4) The test organisms most sensitive to suspended bentonite were 6- to 8-cm shiner perch *Cymatogaster aggregata*. As with *M. saxatilis*, increasing suspended bentonite concentration and decreasing dissolved oxygen and temperature combined in a complex manner to reduce survival. The slightly lower mortality of both species of fish at higher temperature was in contrast to all the invertebrates.

5) In none of the experiments did the 10-day LC50, LC20, or LC10 values bear any predictable mathematical relationship to one another. This illustrates the necessity for studying the tolerance of the most sensitive members of a population.

6) Tolerance to suspended bentonite seemed to be correlated with normal habitat of the organisms, but no phylogenetic correlations were apparent. No species living primarily in close association with mud bottoms was found to be sensitive. All sensitive test species were either invertebrates occurring predominantly on sandy bottoms or in fouling communities, or fish not intimately associated with the bottom.

7) The results indicate that the biological impact of high concentrations of suspended solids would be less severe in winter than in summer. The typically higher dissolved oxygen levels would increase the survival ability of all species studied. Low temperatures would increase the suspended-solids tolerance of the invertebrates, but slightly decrease that of the fish. However, this slight reduction would likely be offset by the increased tolerance at high dissolved oxygen levels.

8) The primary emphasis of this study was mortality of adult macrofauna. It cannot be overemphasized that low mortality of adults in 10 days does not imply the absence of ecologically significant effects. Reduced reproductive success, in terms of spawning adults, eggs, larvae, or juveniles, may be of greater ecological importance than the death of part of the existing population.

4.2 Geological Oceanography

This section discusses the characteristics of the seafloor in the test area, stratigraphy of the upper strata as revealed through subbottom profiling, and sediment properties based upon analyses of vibracores. A prime objective of Project NOMES was a consideration of the potential of test mining to release trace metals or other pollutants to the water column. Additional objectives included the delineation of the deposit in adequate detail to assure that it was commercial in character and that a prediction could be made as to the nature of the discharge plume at the point of discharge from the hydraulic dredge.

4.2.1 Bathymetry

The bathymetric measurements obtained during subbottom profiling, which are discussed later, revealed an irregular bottom topography with NNW.-trending ridges interspersed with circular and eliptical depressions (fig. 19). The area to be excavated during the planned test mining (shaded area in fig. 19) had a relief of 3.4 m and so was considered a realistic choice for operation of the hydraulic dredge.

The shape of the seafloor is characteristic of an area that has experienced glacial scouring and sediment deposition, as well as post-glacial stream channeling and subsequent modification of bottom contours by advancing post-glacial seas.

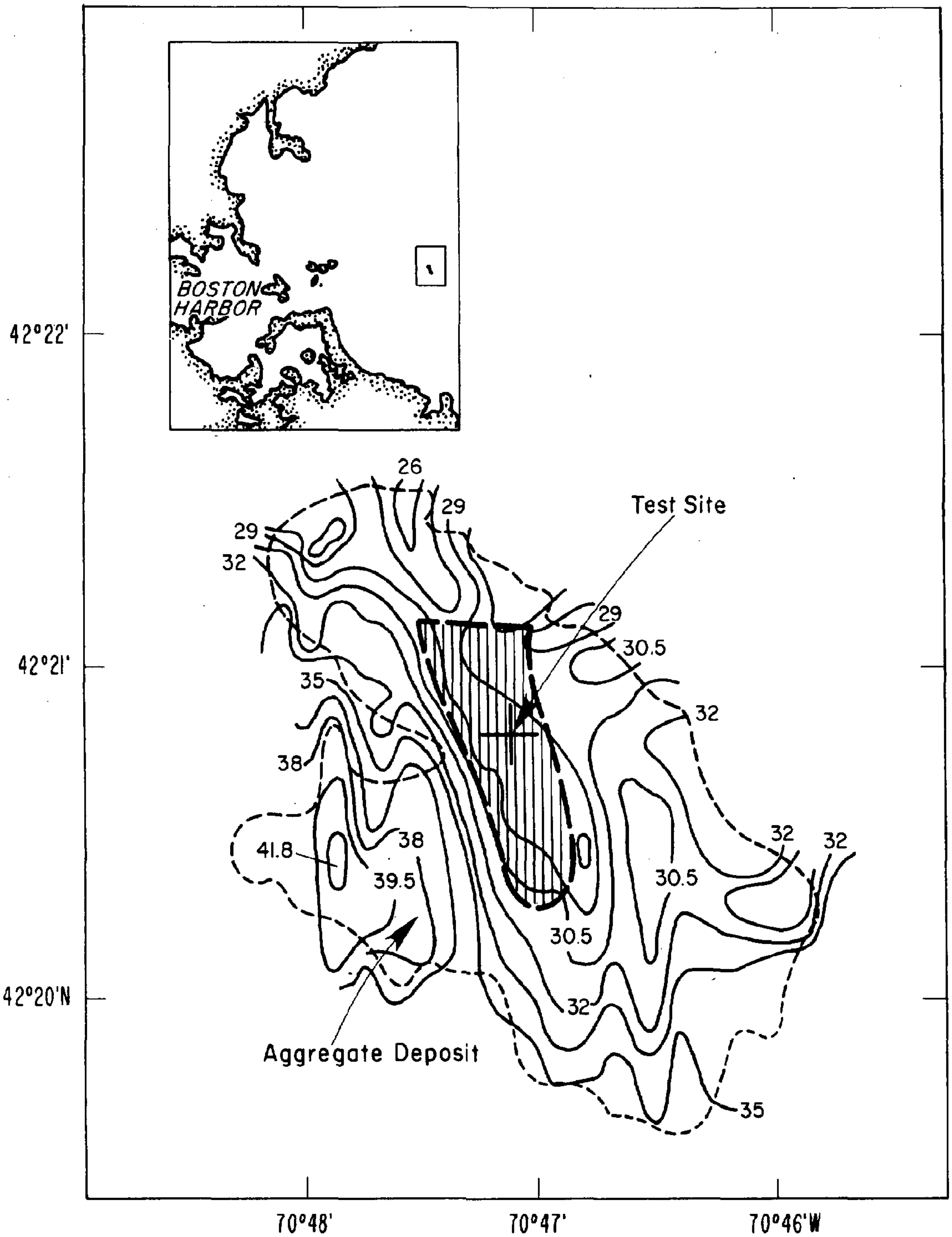


Figure 19. NOMES Project area and area of planned test mining. Contours in enlarged section show water depths in meters, referenced to high water.

4.2.2 Stratigraphy

A pre-NOMES survey conducted for the Massachusetts Division of Mineral Resources in early 1972 located the NOMES sand and gravel deposit through subbottom profiling, side-scan sonar, and two 12-m vibracores. In August 1972, 37 additional subbottom profiles were run, and 31 4-m vibracores were drilled in the vicinity of the deposit. Figures 20 and 21 show the locations of the core sites and subbottom profile tracklines.

For the purpose of identifying those areas within the NOMES deposit that offered characteristics with the best potential for test mining (i.e., thickness of aggregate, commercial quality of sediment, water depth at mean high water, and distance to glacial till outcroppings) three sediment distribution maps were prepared: surficial, subsurface (-1.5 m), and subsurface (-3 m). Core analysis data, reported below, augmented the geophysical records in the preparation of the maps.

The surficial sediment map (fig. 22) was produced from subbottom profiling records, core sample analyses, and information from television observations, as well as diver samples and observations. Classification of sediment types was based on the scheme shown in Table 21, which was modified from a system in use in the Gulf of Mexico (Louisiana Wild Life and Fisheries Commission, 1971). From figure 22 it can be seen that the seafloor in the test site area consists of a patchwork of mixtures of sand, gravel, mud, and glacial till.

Table 21. Sediment Classification

	% Gravel	% Sand	% Mud
Gravel	75 - 100	0 - 25	0 - 25
Sandy Gravel	33.5 - 75	12.5 - 50	0 - 33.5
Muddy Gravel	33.5 - 75	0 - 33.5	12.5 - 50
Sand	0 - 25	75 - 100	0 - 25
Gravelly sand	12.5 - 50	33.5 - 75	0 - 33.5
Muddy Sand	0 - 33.5	33.5 - 75	12.5 - 50
Mud	0 - 25	0 - 25	75 - 100
Gravelly Mud	12.5 - 50	0 - 33.5	33.5 - 75
Sandy Mud	0 - 33.5	12.5 - 50	33.5 - 75
Till	Mixture of boulders, cobbles, gravel, sand, mud		

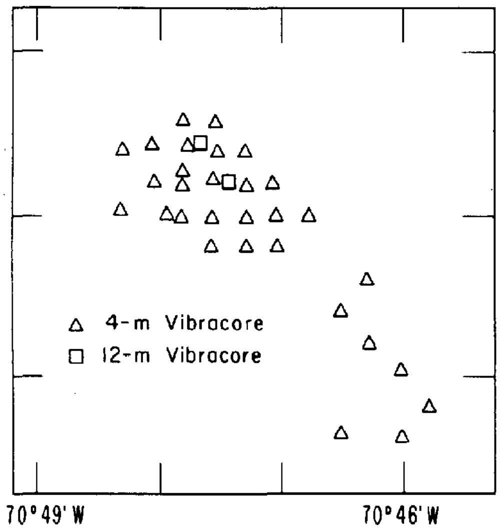


Figure 20. *Locations of the vibracores taken in the NOMES site for NOAA (4-m) and for the Massachusetts Division of Mineral Resources (12-m).*

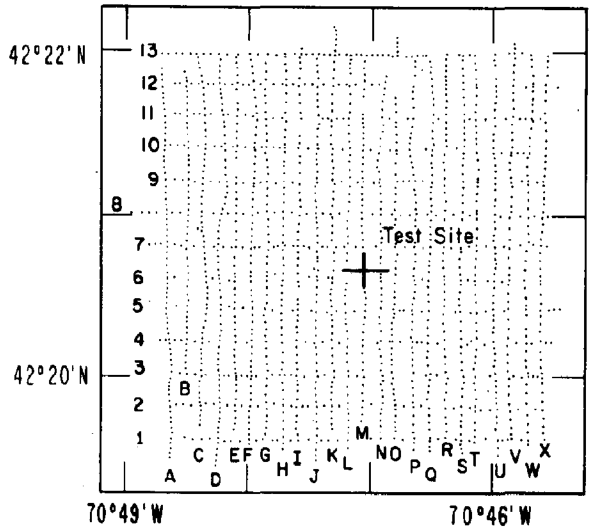


Figure 21. *Ship tracks of the subbottom profiles.*

The sediment distribution 1.5 m beneath the seafloor (fig. 23) is similar to that of the seafloor in that sandy gravel and gravelly sand are still distinct; also the muddy area remains in the northeast corner of the deposit. The overall size of the deposit is smaller, however.

The sediment distribution 3 m beneath the seafloor (fig. 24) shows a greatly diminshed area of sandy gravel. The extent of glacial till, which underlies most of the test site area, becomes more evident.

The subbottom profiling records, coupled with the core analyses, permitted an estimate of the thickness of the area to be mined (fig. 25). It appeared that the deposit contained over 5 million cubic meters of sand and gravel, considerably more than the three-quarter million planned for excavation during the mining test.

Although the main interest in the stratigraphy of the NOMES area was the upper few meters, the subbottom profiling records revealed several distinct formations: Carboniferous Cambridge argillite, undifferentiated Pleistocene glacial drift, two Pleistocene marine "clays," and Holocene sand and gravel (fig. 26). The section lines used to develop figure 26 are shown in figure 27.

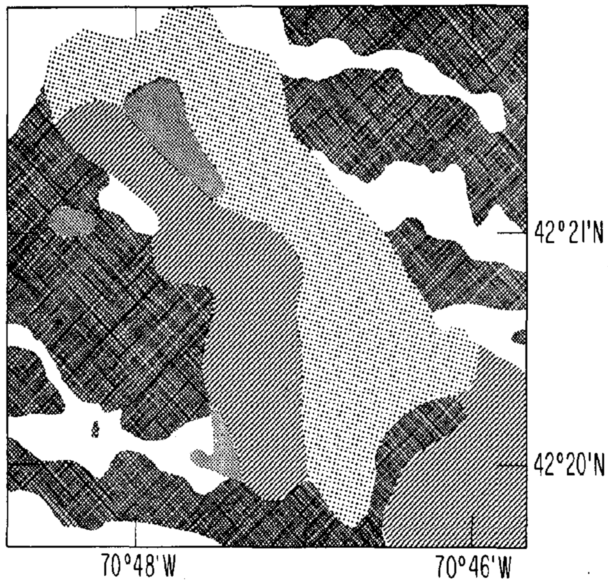


Figure 22. Surficial sediment distribution in NOMES Project area.

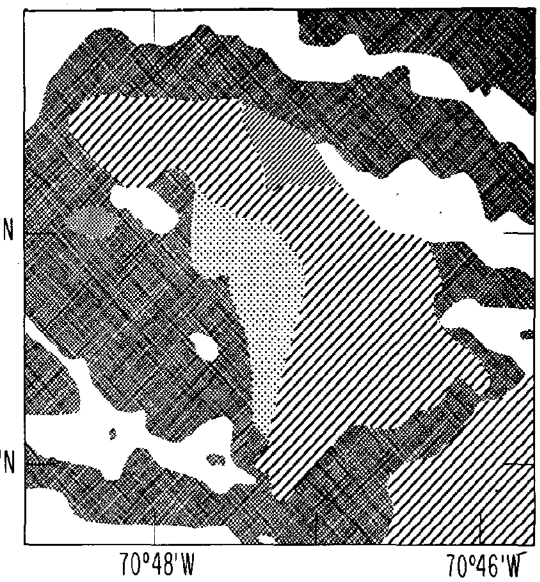


Figure 23. Subsurface (-1.5 m) sediment distribution in NOMES Project area.

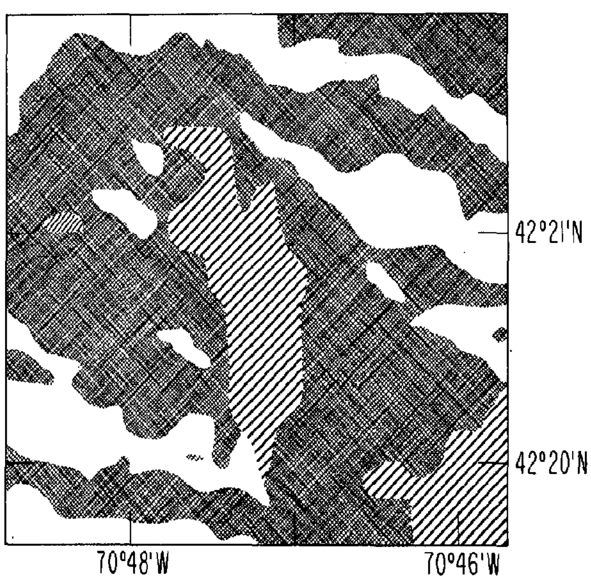
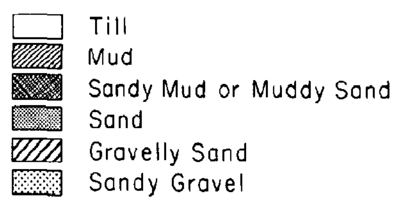


Figure 24. Subsurface (-3 m) sediment distribution in NOMES Project area.



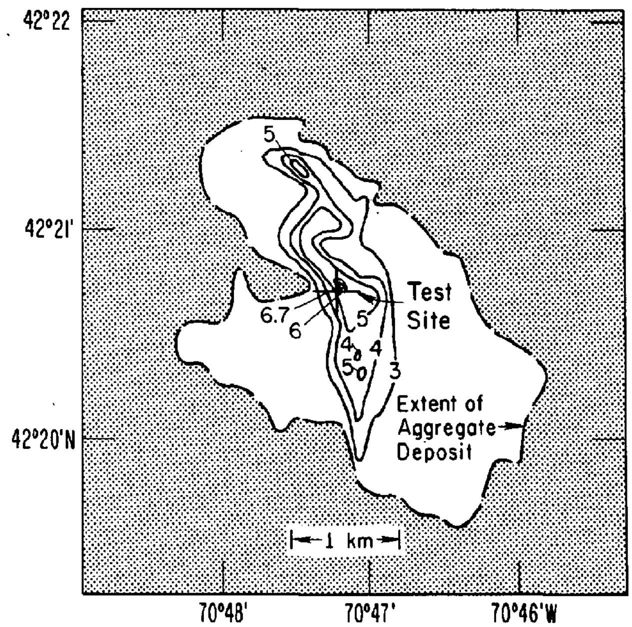


Figure 25. Aggregate isopach map of the experiment area (deposit contoured in meters).

The Cambridge argillite outcrops on several Boston Harbor Islands and is believed to underlie the NOMES area as bedrock. It is overlain by Pleistocene glacial till, a heterogeneous mixture of boulders, gravel, sand, silt, and clay ranging in thickness from a thin veneer to nearly 30 m. Two marine clays, separated by an erosional uncomformity, overlie the glacial till.

The "NOMES deposit" appears to be a gradational feature resting on, and yet geologically part of, the upper marine clay.

4.2.3 Core Analyses

Of the 31 cores acquired by vibratory coring (fig. 20), 10 were selected for detailed laboratory characterization. Mineralogy, chemistry, and trace metal properties were examined.

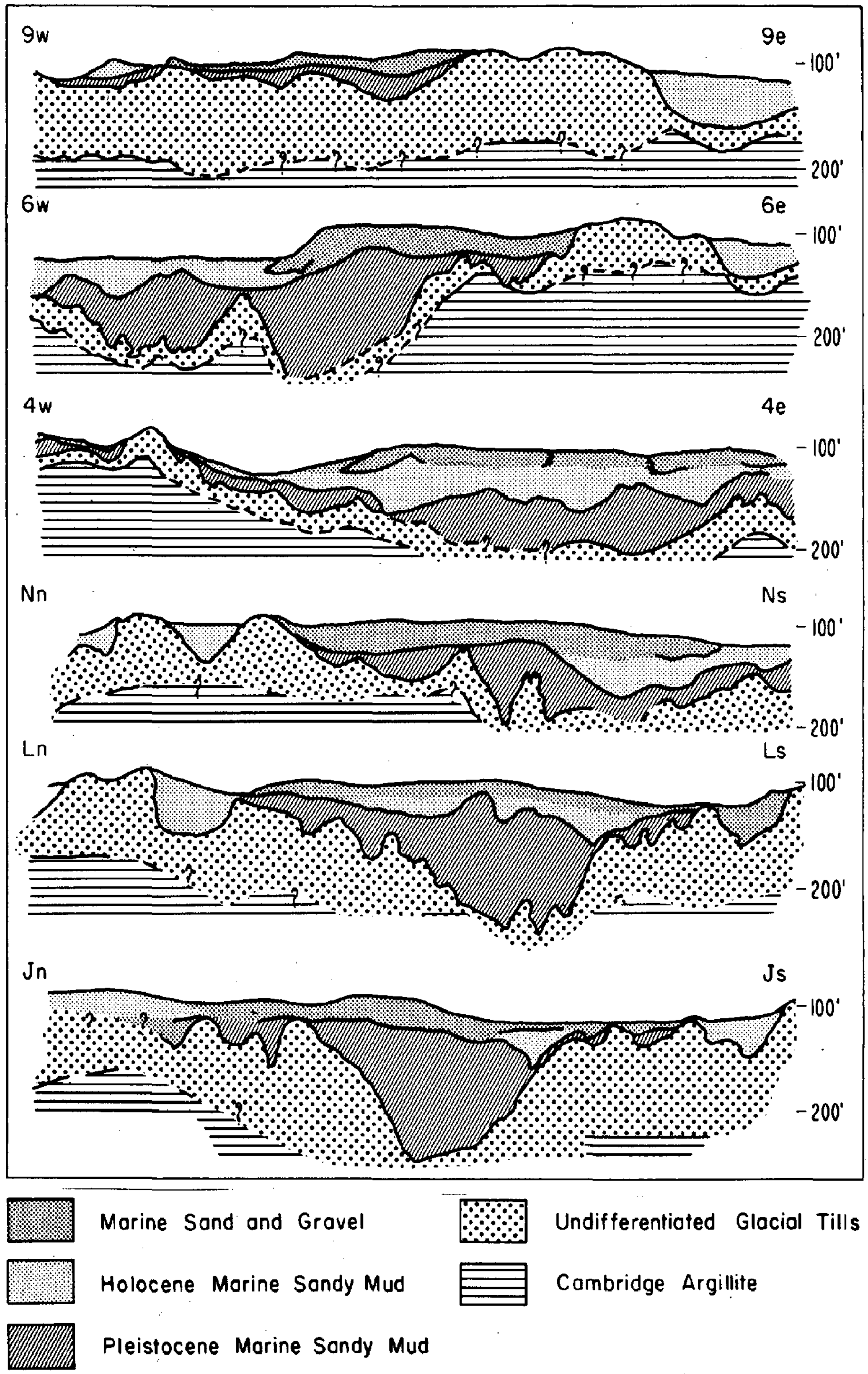


Figure 26. Selected geological cross sections through the NOMES site.

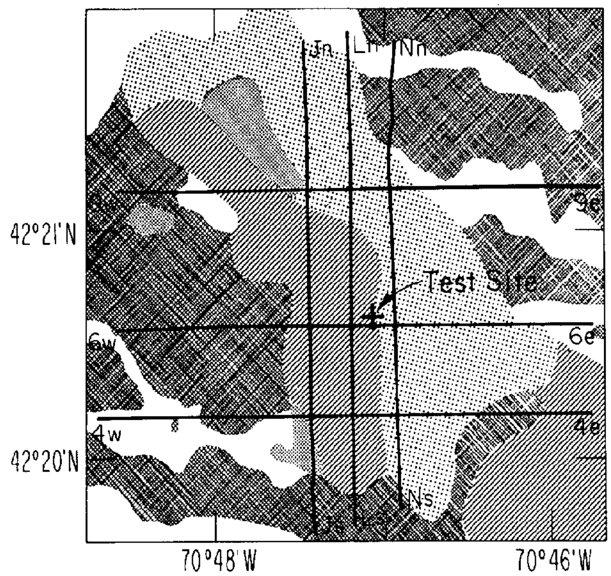


Figure 27. Locations of tracklines used as a basis for cross sections in Figure 26.

Mineralogy

The general appearance of the -10, +230 mesh material from several strata of all 10 cores was similar; therefore, only a single description is given. The particles were subrounded to subangular. The predominant minerals and their percentages were as follows:

Feldspar, 25-30%	(Primarily plagioclase and some orthoclase)
Quartz, 20-30%	(50% clear-to-milky, and 50% stained dull yellow)
Hornblende, 15-20%	
Mica, 5-10%	(Biotite and muscovite)

In addition, the minor minerals included some opaques, garnet, tourmaline, and possibly olivine. There were a few rock fragments that appeared to be granitic grains. The organics included about 5% shell fragments plus *Foraminifera* tests.

The predominant -230 mesh mineral was quartz.

Sedimentological characteristics are not included in this report but generally reveal what we would expect from a heterogeneous glacial deposit: very poorly sorted sediments.

Chemistry

Chemical analyses of the sediments to be disturbed by test mining were examined to learn something about their pollution potential. The -230-mesh size range was of special importance because, even though it constituted only 3% of the deposit, it is the size that would overflow the hydraulic dredge to form the particulate component of the discharge plume.

Morphological description, depth, and color are given for each core stratum in Table 22.

Moisture determinations. These results were used only for correcting moist sample weights to dry weights. The values averaged about 30% for the -230-mesh material.

Sulfide analyses. The easily available sulfide concentrations found in all of the samples were below 2 mg/kg. These samples have very low values compared with sediments from other sites along the New England coast where it is common to find one hundred to five hundred times this concentration. Since sulfides are stable only under strongly reducing conditions (JBF Scientific Corp., 1973), it was concluded that the strong currents and extensive mixing in Massachusetts Bay prevent such anoxic conditions at the water-sediment interface, at least in the area sampled. Consequently, the release of heavy metals from both inorganic and organic sulfides would not appear to be a serious problem when the discharge plume enters oxygen-rich surface waters.

Total phosphorus analyses. The phosphorus concentrations in the -230-mesh material were also very low. All values were below 10 mg/kg except for the top layer of core 9-I-1, where a value of 14 mg/kg was found. Apparently the small concentrations of well-stabilized organic matter contained very little phosphorus, and the clay and silt mineral fraction in this area also was relatively low in phosphorus. This observation is compatible with the fact that the predominant -230-mesh mineral was quartz.

Extractable metals. The concentrations of 0.1N HCl-extractable major and minor metals are shown in Table 23. The major metal concentrations have been corrected by subtracting the amounts contained in the residual moisture, assuming it had the same composition as the free pore water.

Examination of the results for the major metals shows that certain cores contained very large concentrations of dilute acid-soluble calcium. These were later shown to be largely from aragonite.

Mercury. Only four -230-mesh samples were analyzed. Three samples were from surficial strata of individual cores, and one was a combination of surficial strata from two cores. The analyses were performed both at the University of New Hampshire and at the U.S. Bureau of Mines. The average concentration found was 0.20 ppm, which is quite normal in view of the estimated lithospheric abundance of 0.5 ppm. The data are summarized in Table 24.

Table 22. Chemical Analyses of Core Strata[(a)]

Stratum Number	Depth (Inches)	Color	Description	-230 Mesh (%)	COD[(b)] (g/kg)	Organic[(c)] Carbon (%)	CEC[(d)] (meq/100g)	Sulfide[(e)] (mg/kg)	Phosphorus[(f)] (mg/kg)	Oil &[(g)] Grease (mg/kg)
				Core 7-I-1						
7-I-2-1-1	0-20	2.5YN/4	Sand-fine to medium coarse. Gravel-to 1.5 inches. Shell Fragments-very coarse.	3.54	30.8	1.15	61.4	<0.05	1.2	<50
7-I-2-2-1	20-37	2.5YN/4	Fine sand-no gravel.				62.0			
7-I-2-2-2	37-44	2.5YN/4	Fine sand & ∿15% 0.75" gravel.				32.0			
7-I-2-3-1	44-54	2.5YN/4	Coarse sand & ∿15% clay.				24.9			
7-I-2-3-2	54-70	2.5YN/4	Fine gravel & ∿10% clay. Becoming gravelly to 0.5".				27.4			
7-I-2-4-1	70-80	5Y5/2	Clay layer with intermittent, discontinuous sand lenses.				15.4			
7-I-2-4-2	80-85	5Y5/2	Medium fine sand.				20.5			
7-I-2-4-3	85-102	5Y5/2	Clay layer with intermittent, discontinuous sand lenses.		8.6	0.32	11.0			
7-I-2-5-1	102-132	5Y5/2	Clay layer with intermittent, discontinuous sand lenses.				11.3			
				Core 7-K-1[(a)]						
7-K-1-1-1	0-14	5Y4/2	Fine sand.	4.40	30.7	1.15	43.1	0.19	--	--
7-K-1-1-2	14-56	5Y4/2	Coarse sand and gravel to 2". Gravel becoming very coarse to 3". (Excellent fill material.)				26.0			
				Core 7-M-1[(a)]						
7-M-1-1-1	0-9	5Y5/2	Fine sand with few shells. Becoming coarse sand.	3.81	26.2	0.98	49.9	<0.05	1.9	<50
7-M-1-1-2	9-13	5Y5/2	Coarse sand and gravel to 0.75"; well graded.				41.4			
7-M-1-1-3	13-29	5Y5/2 ↓ 2.5YN/4	Coarse gravel to 2.5"; very well graded. Small amount of clay.				25.2			
				Core 8-I-1[(a)]						
8-I-1-1-1	0-12	5Y5/1	Fine sand and shell fragments.	4.50	36.3	1.36	53.6	0.86	3.4	<50
8-I-1-1-2	12-30	5Y5/1	Sand and gravel to 2". Well graded; sand becoming coarse.				61.2			
8-I-1-2-1	30-39	5Y5/2	Sand and gravel to 1.5". Well graded. Some shell fragments.				57.1			
8-I-1-2-2	39-50	2.5Y5/2	Fine sand and shell fragments.		33.9	1.27	68.5			
8-I-1-2-3	50-60	2.5Y5/2	Becoming gravel to 2". Shell fragments to 0.5".				56.3			

Table 22. (Continued)

Stratum Number	Depth (Inches)	Color	Description	-230 Mesh (%)	COD[b] (g/kg)	Organic[c] Carbon (%)	CEC[d] (meq/100g)	Sulfide[e] (mg/kg)	Phosphorus[f] (mg/kg)	Oil & Grease[g] (mg/kg)
				Core 8-K-1[a]						
8-K-1-1-1	0-11	5Y5/2	Well graded sand and gravel to 2".	4.12	44.7	1.68	50.4	0.15	2.4	--
8-K-1-1-2	11-22	5Y4/1	Gravel as above but sand becoming finer.				32.5			
8-K-1-2-1	22-41	2.5YN/4	Medium coarse sand and gravel to 2". Fine sand layers of 2-3" with small shell fragments and slight color change from light to dark gray.				27.5			
				Core 8-M-2[a]						
8-M-2-1-1	0-18	5Y4/2	Sand and gravel to 1.5", well graded.	0.94	55.3	2.07	61.3	0.36	2.0	<50
8-M-2-1-2	18-40	2.5Y4/2	Sand with 10-15% gravel and large shell fragments.				34.0			
8-M-2-2-1	40-74	2.5Y4/2	Very coarse sand-no gravel-large shell fragments.				65.0			
8-M-2-3-1	74-84	2.5Y4/2	Considerable clay and silt		37.2	1.40	17.0	1.8		
8-M-2-4-1	84-110	2.5Y4/2	Silty clay.		29.9	1.12	15.8	0.84		
				Core 8-O-1[a]						
8-O-1-1-1	0-28	5Y6/2	Excellent sand and gravel to 2.5". Well graded.	2.30	14.7	0.55	35.0	0.48	0.90	<50
				Core 9-I-1[a]						
9-I-1-1-1	2-38	5Y5/1	Fine sand and ~25% gravel to 1.5". Heavy shell fragments.	5.00	33.6	1.26	57.7	0.34	14.	<10
9-I-1-3-1	38-45	2.5YN/5	Silty clay and fine sand.				28.6			
				Core 10-G-1[a]						
10-G-1-1-1	0-10	5Y5/1	Old beach sand.	2.32	17.1	0.64	30.3	1.4	2.5	--
10-G-1-1-2	10-18	5Y5/1	Coarse sand and gravel to 1.5". Well graded.				30.0			
				Core 11-E-1[a]						
11-E-1-1-1	0-23	2.5YN/4	Clayey sand and ~20% gravel to 1.5" with shell fragments. Changing to less gravel.	14.7	17.5	0.66	54.0	0.37	1.5	<5
11-E-1-2-1	23-83	2.5YN/5	Very stiff silty clay with occasional fine sand lenses.				11.8			

(a) All results based on oven dry weight (103°-105°C)
(b) Chemical Oxygen Demand of -230 mesh material.
(c) Calculated from COD results.
(d) Cation Exchange Capacity of -230 mesh material. These results are high in some cases. See text.
(e) Based on "grab" samples taken prior to screening.
(f) Total phosphorus after destruction of organic matter--based on -230 mesh material.
(g) Freon extractable from -230 mesh material.

Table 23. Amounts of Metals (ppm) Extracted From Sediment by Hot 0.1N HCl

Stratum Number	Major Elements (Partial)†				Minor Elements									
	Na	Mg	Ca	K	Fe	Mn	Zn	Cu	Ni	Pb	Cr	Cd	Co	Be
7I-2-1-1	170	1,430	37,500	847	359	13	16	4.7	5.6	15	4.4	1.2	3.1	N.D.
7I-2-2-1					726	19	9.4	3.3	4.8	8.5	2.7	0.54	2.6	N.D.
7I-2-2-2	2,070	1,640	6,980	1,170	4,640	68	24	9.1	9.9	11	3.4	0.22	4.7	0.41
7I-2-3-1					6,770	97	24	9.4	12	10	5.9	0.38	5.3	0.49
7I-2-3-2*	356	2,810	4,740	2,220	8,480	128	30	6.6	15	12	10	0.33	6.4	0.62
7I-2-4-1			2,290	4,800	11,100	170	39	19	19	12	18	0.37	7.7	0.68
7I-2-4-2					8,620	137	32	12	17	11	13	0.30	7.2	0.59
7I-2-4-3	741	2,350	2,010	2,050	7,020	131	26	20	14	10	7.7	0.17	6.6	0.52
7I-2-5-1	635	2,750	1,570	2,000	7,790	171	30	22	16	11	9.1	0.19	7.4	0.64
7K-1-1-1	468	859	23,700	434	409	15	5.7	2.1	3.5	5.9	2.3	0.65	2.0	0.13
7M-1-1-1	546	744	37,400	452	984	22	8.5	7.1	4.9	16	5.4	0.89	2.9	N.D.
8I-1-1-1*	1,140	954	24,500	613	1,130	55	20	9.5	5.4	29	5.1	0.80	2.9	0.08
8I-1-1-2**					165	8.1	2.1	2.1	3.1	6.3	2.5	0.46	1.8	N.D.
8I-1-2-1**			22,000	589	181	7.3	1.4	1.4	2.4	4.8	2.0	0.37	1.6	N.D.
8I-1-2-2**			33,700	900	427	14	3.0	2.0	3.8	6.8	2.7	0.56	2.2	N.D.
8I-1-2-3**	520	650	26,200	450	104	8.1	1.3	1.1	2.6	5.3	2.4	0.47	1.6	N.D.
8K-1-1-1	972	3,470	9,250	1,450	1,050	202	56	23	17	62	38	0.87	7.0	0.75
8M-2-1-1	619	1,540	18,400	644	3,740	70	106	14	11	67	8.7	0.71	4.4	0.58
8O-1-1-1	551	587	32,000	424	298	19	5.6	10	4.1	12	3.2	0.74	2.5	N.D.
9I-1-1-1	185	395	31,600	545	363	13	3.6	2.3	3.7	10	2.4	0.67	2.1	N.D.
10G-1-1-1	970	2,330	10,200	774	8,720	86	43	27	16	39	13	0.72	7.2	0.52
11E-1-1-1	34	2,100	8,160	1,550	5,330	83	27	14	13	17	6.9	0.44	5.1	0.51

* Trace elements determined in duplicate.
** Trace elements determined in triplicate.
N.D. = Not detected (<0.05 ppm for Be).
† Values have been corrected by subtracting the amounts of these elements assumed present in the moisture (assumed to have the composition of typical sea water).

Table 24. Mercury Content of Four -230 Mesh Sediments

Sample	Parts Per Million Mercury		
	UNH	U.S. Bureau of Mines	Average
7-I-2-1-1	0.41	0.37	0.39
7-M-1-1-1	0.13	0.11	0.12
8-I-1-1-1, 8-O-1-1-1 →	0.23	0.19	0.21
11-E-1-1-1	0.08	0.11	0.10

Oil and grease. During the test mining, a large amount of "Never-Seez" lubricant was to be used. The organic portion of this lubricant was found by infrared analysis to be a simple aliphatic hydrocarbon. The inorganic portion was primarily an aluminum silicate with small amounts of copper, zinc, and other trace metals present. A "tool oil" was also expected to be in use. Infrared analysis of this oil indicated that it was also primarily a simple aliphatic hydrocarbon. Both of these materials would be readily recovered by the oil and grease extraction procedure, and therefore any large increase during dredging would be detected.

The baseline levels found in the surficial sediments were extremely low, showing no significant oil and grease present prior to mining.

Chemical oxygen demand. The concentrations reported in Table 22 show very low values, characteristic of stable sediment uncontaminated by significant amounts of fresh organic matter such as sewage. As expected, the highest concentrations were found in the surficial strata. The empirical conversion to percent organic carbon yielded only one value as high as 2%, and this is still very low for -230-mesh material. Obviously these sediments would not contribute heavy burdens of unstable (decomposing) organic matter to the water column if they were discharged at the surface.

Cation exchange capacity. In spite of experimental difficulties with this analysis, it can be said that values are highest where the calcium concentrations are highest, although the values are inaccurate because of aragonite dissolution. Where the calcium concentrations are low, the values are in the range of 10-30 meq/100 g. Such values do not suggest that the discharge plume would have an inordinately large adsorptive capacity that could promote a deficiency of dissolved nutrients in the water column.

X-ray diffraction analysis. Material from cores 11-E-1 and 7-I-2 were analyzed. Comparison of the spectra from the samples saturated with ethylene glycol with the spectra of the nonsaturated samples indicated that the clay was a nonexpanding clay. The major components of the substances in all core samples were quartz, illite, and unweathered feldspars.

The 7-I-2-1-1 core material was analyzed because of the need to determine if the large amount (3.7%) of calcium was from aragonite. Here a problem was encountered, arising from the near coincidence of the three strongest lines of aragonite with two lines of quartz and one of illite.

The line at $2\theta = 33.18^\circ$, $d = 2.700$ is characteristic of aragonite but not quartz or illite. However, this line alone is not sufficient to identify aragonite. Slowing the scan speed to 0.2°/min allowed the two aragonite lines at 26.24° and 27.25° to appear as shoulders on the quartz 26.66° and illite 26.77° lines, which were not resolved. That these shoulders are due to aragonite was shown by a slow scan in this 2θ region of sample 11-E-1-2-1, which has a low amount of calcium. No shoulders appeared. A slow scan from 33.00° to 33.50° also showed the absence of the 33.18° aragonite peak that is present in the 7-I-2-1-1 spectrum. It was concluded that aragonite was present in core sample 7-I-2-1-1.

Pesticides and polychlorinated biphenyls. A summary of the compounds found and the detection limits for the method is given in Table 25. On the basis of these data, we conclude that the levels of chlorinated hydrocarbon pesticides and PCB's are very low and the discharge plume would not contribute hazardous amounts of these substances to the water column.

Trace metals

The concentrations of dissolved trace metals in seawater are known to be affected by interactions with suspended particles of sediment, such as would be present in a hydraulic dredge discharge plume. Krauskopf (1956) showed that copper, zinc, and lead are adsorbed more strongly than other metals he studied. He concluded that adsorption processes are of great importance in controlling trace metal concentrations in seawater.

Two types of environmental effects could be associated with mining by hydraulic dredge: initial agitation of the sediments could release trace metals to the marine environment; and trace metals could be adsorbed by particles in the discharge plume. Investigations were conducted into both areas of concern, using the -230-mesh size range expected to occur in the discharge plume.

Before attempting any investigation of the adsorptive properties of the bulk sediment, an experiment was conducted to determine if the trace metals were desorbed while being agitated in seawater. This experiment was conducted at both 20°C and at 4°C, to simulate surface water and bottom water temperatures respectively, using a concentration of 15 g of -230-mesh sediment per liter of seawater. Agitation was accomplished with magnetic stirring. After 3 hr, the seawater was separated from the sediment by filtration. The concentrations of Cu, Pb, Ni, Co, Cd, and Zn were determined in each filtrate and in a portion of the same seawater used for the experiment.

*Table 25. Concentrations of Chlorinated Hydrocarbon Pesticides and Polychlorinated Biphenyls in Several Surficial Core Samples***

Sample	Depth (Inches)	Pesticide	Concentration (Parts Per Billion)	PCB	Concentration (Parts Per Billion)
7-I-1-1-1	0-8.5	pp'DDT pp'DDD pp'DDE op'DDT	4.1 0.22 1.7 0.24	Aroclor 1260	41
7-K-2-1-1	0-3	pp'DDE	0.26	*	*
8-I-4-1-1	0-20	None detected		*	*
8-M-1-1-1	0-24	pp'DDT pp'DDD pp'DDE	0.43 0.18 0.69	*	*
8-O-4-1-1	0-24	pp'DDT pp'DDD pp'DDE op'DDT	0.27 0.25 1.5 0.24	Aroclor 1254	13
10-G-3-1-1	0-20	None detected		*	*

* Evidence that these samples contain Aroclor 1254 near the detection limit of 10 parts per billion.

** The estimated detection limits for all compounds sought in parts per billion are shown below.

Heptachlor	- 0.04	Aroclor 1248	- 10
Aldrin	- 0.05	Aroclor 1254	- 10
DDA	- 58.	Aroclor 1260	- 10
Dilan	- 0.55		
Methoxychlor	- 1.3		
pp'DDT	- 0.27		
pp'DDD	- 0.18		
pp'DDE	- 0.10		
op'DDT	- 0.24		
op'DDD	- 0.26		
op'DDE	- 0.20		

Results are summarized in Table 26. Each datum represents the average of independent duplicate determinations. It is apparent that none of the trace metals were desorbed during a 3-hr equilibration, which suggests that the specific discharge plume expected to result from the test mining would be unlikely to induce significant trace metal contamination to the surface water by a desorption mechanism.

Adsorption experiments were addressed to predicting the effect on the water column of the fine particles in the discharge plume, which could remain in suspension for several days before redepositing on the seafloor. In addition to temperature, the effects of light intensity and oxygen content, also known to differ substantially from seafloor to water surface, were examined.

Preliminary experiments were conducted at room temperature with no attempt to control the oxygen level of the seawater. These experiments were conducted in a 4-gal polypropylene bucket containing 10 ℓ of suspension at a concentration of 15 g/ℓ of -230-mesh sediment. Agitation was accomplished with a motor-driven polypropylene stirrer. At the start of the experiment, the suspension was spiked with 100 µg/ℓ of each of the six elements. Samples were withdrawn after 30 min and then every hour on the hour for 7 hr. The results, in terms of percent adsorption of added metal as a function of time, based on triplicate trials, are plotted for cobalt, nickel, cadmium, zinc, copper, and lead in figure 28. Very strong adsorption was observed for copper, lead, and cadmium; moderately strong adsorption was observed for zinc, and significantly weaker adsorption for cobalt and nickel.

Table 26. Desorption Of Metals By Seawater From Bulk Sediment After 3 Hours Agitation

Metal	µg/ℓ in filtrate		µg/ℓ in Seawater
	20°C	4°C	
Cu	1.5	1.5	1.5
Pb	2.0	2.0	2.0
Ni	2.0	1.6	2.0
Co	1.0	1.0	1.0
Cd	1.0	1.0	1.0
Zn	1.8	2.2	2.4

It is likely that the adsorption process was incomplete for the less strongly adsorbed metals. Therefore, duplicate 6-day equilibrations were conducted in 4-ℓ polypropylene beakers. Table 27 compares the residual concentrations of the various metals in solution after 7 hr and after 6 days with the experimentally determined concentrations in the seawater used for these experiments. For copper and cadmium, no significant change in concentration was observed between 7 hr and 6 days. For lead and zinc, there was a small but significant decrease in concentration; nickel and cobalt exhibited a large decrease in concentration. The 6-day equilibrium concentrations for copper and lead are not significantly different from the concentrations in normal seawater. In the case of cadmium and zinc, the 6-day equilibrium samples showed small increases over normal seawater. In contrast, nickel and cobalt showed substantially larger concentrations than normal seawater, strongly suggesting that equilibrium for these two elements had not yet been reached in 6 days.

In all equilibrium experiments, the order of trace metal adsorption was the same. The order (Table 28) was Cu = Pb > Cd > Zn > Ni > Co, which is in general agreement with Krauskopf's (1956) adsorption studies in seawater using several different adsorbents.

Considering the rapid adsorption of Pb, Cu, Cd, and Zn on natural sediment for most environmental conditions, it is unlikely that the concentrations of soluble species of these metals will be greatly altered in the water column.

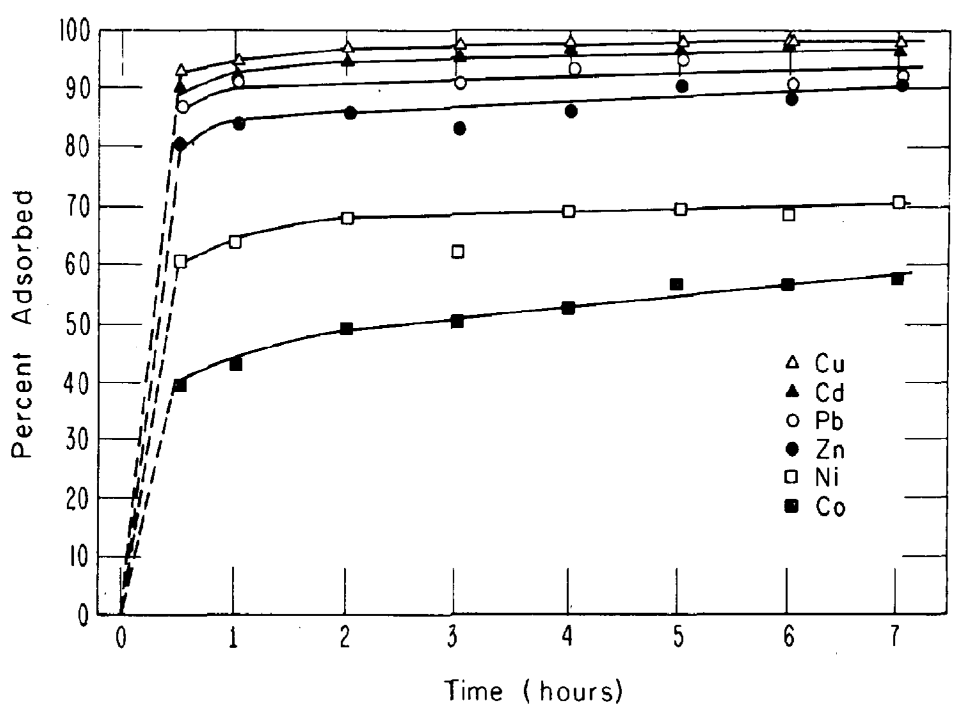


Figure 28. Percent added metal adsorbed by sea water, as a function of time, for cobalt, nickel, cadmium, zinc, lead, and copper.

Table 27. Metal Concentrations In Seawater Before And After Equilibration At 25°C

Metal	Concentration in Seawater Spiked with 100 μg/ℓ (μg/ℓ) after 7 hrs	Concentration in Seawater Spiked with 100 μg/ℓ (μg/ℓ) after 6 days	Concentration in Normal Seawater (μg/ℓ)
Cu	2.0	2.5	1.9
Pb	6.5	2.8	2.4
Ni	30.0	11.0	1.8
Co	43.0	10.0	1.0
Cd	3.0	3.0	1.0
Zn	10.0	4.2	2.1

Table 28. Order of Adsorption After Three Hours

Experimental Conditions	Order Adsorbed (% adsorbed)
20°C, pH 7.9, Dark	Cu=Pb=Cd > Zn > Ni > Co 98=99=98 > 93 > 67 > 47
4°C, pH 7.9, Dark	Cu=Pb > Cd > Zn=Ni > Co 98=96 > 58 > 36=39 > 29
20°C, pH 8.6, Dark	Cu=Pb=Cd > Zn > Ni > Co 97=95=99 > 94 > 70 > 49
4°C, pH 8.6, Dark	Cu=Pb > Cd > Zn > Ni > Co 98=94 > 64 > 46 > 36 > 24
4°C, pH 7.9, Light	Cu=Pb > Cd=Zn > Ni > Co 97=93 > 30=28 > 23 > 9
20°C, pH 8.6, Light	Cu=Pb=Cd=Zn > Ni > Co 96=97=97=94 > 74 > 50
4°C, pH 8.6, Light	Cu=Pb > Cd > Zn=Ni > Co 97=94 > 76 > 46=42 > 26
20°C, pH 7.9, Light	Cu=Pb=Cd > Zn > Ni > Co 97=95=94 > 87 > 63 > 38

4.2.4 Discussion

The site selected for the mining test was found by subbottom profiling and delineated through core sampling. Its characteristics were those of a commercial deposit with respect to aggregate type, amount of fine material, quantity of aggregate, water depth, and nearness to market. An analysis of the sediments to be mined during the test, with emphasis on the -230-mesh size range (which was expected to overflow the hydraulic dredge and constitute the particulate phase of the discharge plume) showed that the test was not likely to increase (or decrease) the trace metal content present in the water column.

4.3 Chemical Oceanography

Field measurements and samples were taken, from November 1970 to August 1973, of total suspended sediment, turbidity, dissolved oxygen, temperature, depth, and salinity. Although some sampling was performed outside the scope of NOMES, sampling took place biweekly, concurrently with NOMES phytoplankton measurements at the 15 locations shown in figure 29.

Water samples were analyzed for nutrients to develop a baseline because the test mining could have added inorganic nutrients to the water column, which might have affected plankton populations. Nitrogen is generally a limiting nutrient for production in coastal waters, so analyses were made for NO_3^- and NO_2^-. Phosphorus is a component of energy transfer compounds such as

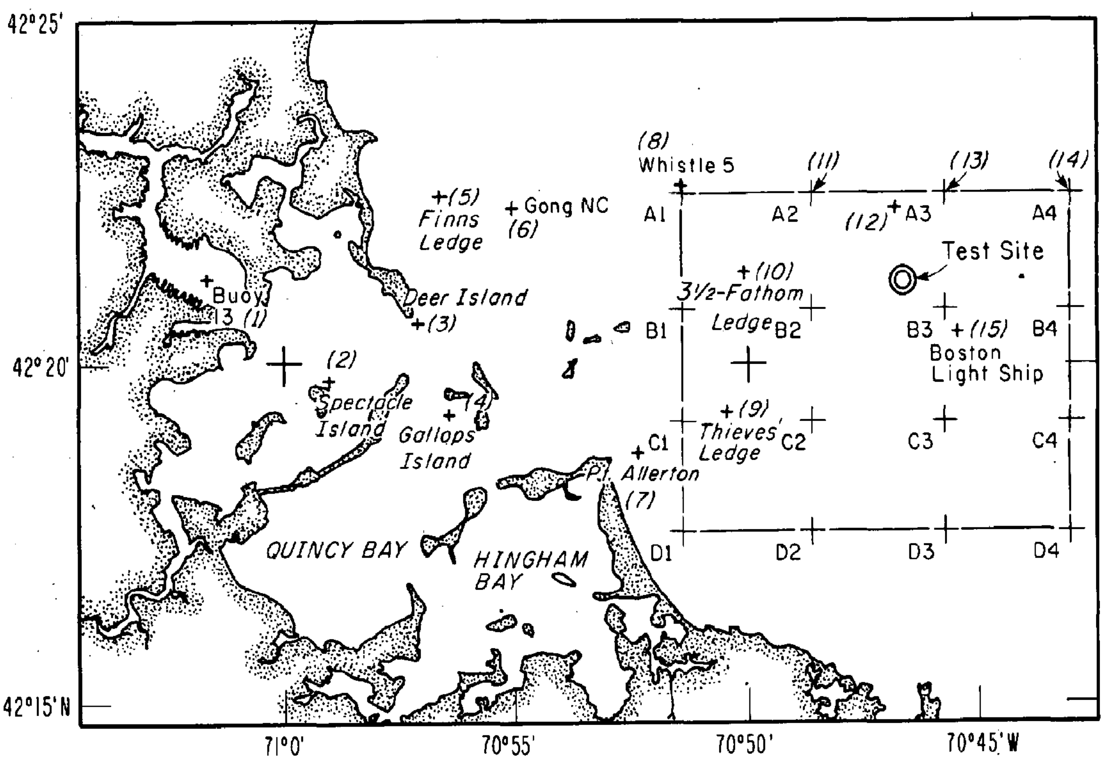


Figure 29. Chemical oceanography sampling locations.

ATP, so $PO_4^{\equiv}$ was determined. Silicon is a basic structural element in the cell walls of diatoms, so SiO_2 was analyzed. Dissolved O_2 also was measured because it is related to phytoplankton productivity and is vital to marine life. A comprehensive report on the findings has been published (Frankel and Pearce, 1973), so only a brief summary is presented here.

4.3.1. Spatial Distribution of NO_3^-, $PO_4^{\equiv}$, and Suspended Solids

Figures 30 to 32 show the concentrations of NO_3^-, $PO_4^{\equiv}$, and suspended solids at the sampling stations in figure 29. Stations are numbered in order of increasing distance from the inner harbor, which is represented as 0. As could be expected, generally the higher concentrations of nutrients and sediments are nearer the harbor.

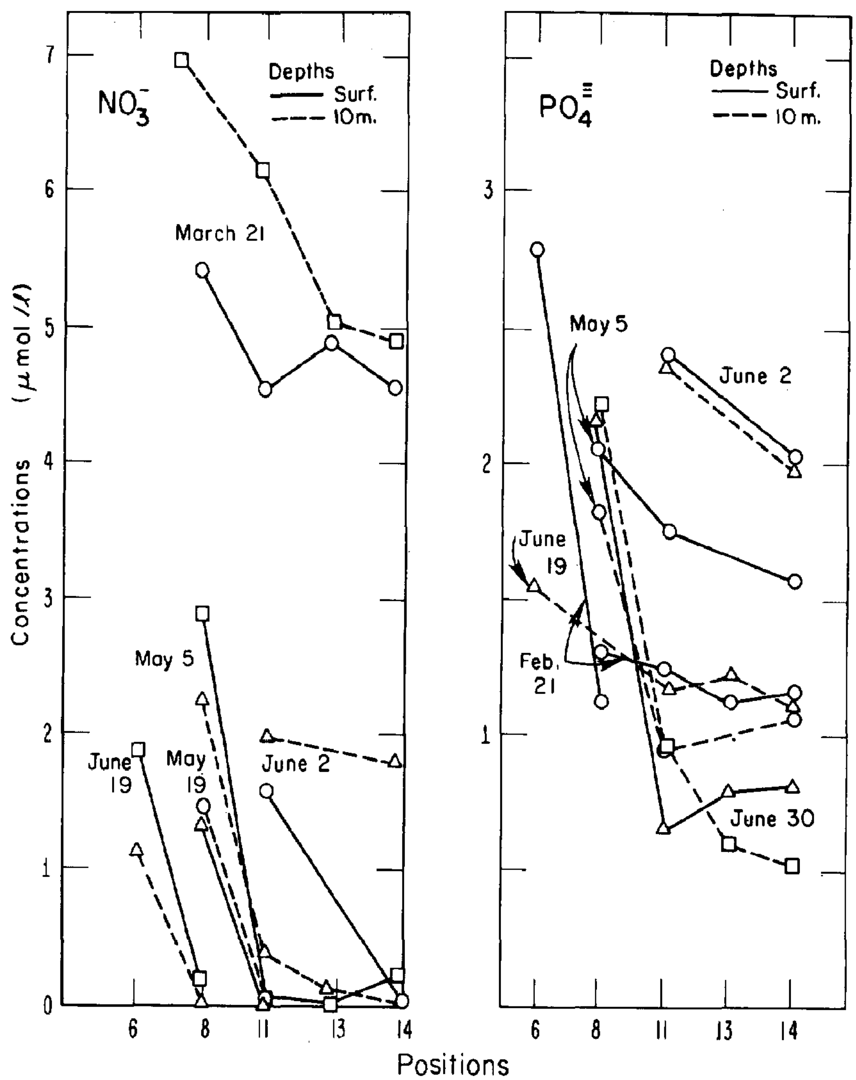


Figure 30. Concentrations of NO_3^- and $PO_4^{\equiv}$ as a function of increasing distance from Boston Harbor.

4.3.2 Time-Variant Trends in Nutrient Concentrations

The time-variant trends in the nutrient concentrations can be seen in figures 33 through 38. To facilitate the coordination of field operations for the various groups working on the NOMES Project, a rectangular grid of stations was set up as shown earlier in figure 12. Stations A1, A4, and B3 were chosen for sample studies of the temporal changes in nutrient concentration patterns. Stations A1 and A4 were representative of the stations closest to land and farthest from land; B3 was near the mine site.

The $N\text{-}NO_3$ concentrations appear to be inversely related to phytoplankton abundance (figs. 33, 35, and 36). Nitrate-nitrogen reaches a peak concentration in winter and then drops to undetectable levels at the time of the spring bloom as the growing phytoplankton population completely assimilates the available nitrate-nitrogen. Nitrites seem to fall in concentration as do the nitrates. Phosphate-phosphorus is in excess even during the bloom (fig. 34). Since phosphorus does not appear to be the limiting nutrient, one could not expect its concentration to fall to negligible amounts during the bloom. The nutrient concentrations that would normally occur in the bay are increased by sewage effluent discharges into the harbor.

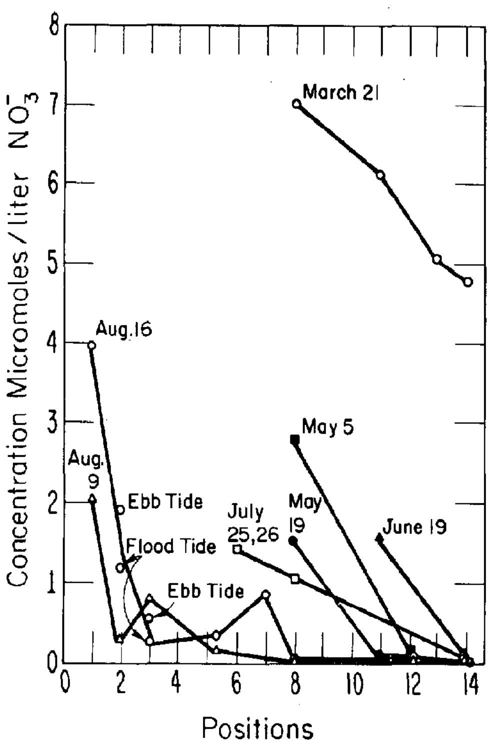


Figure 31. Concentrations of NO_3^- as a function of increasing distance from Boston Harbor.

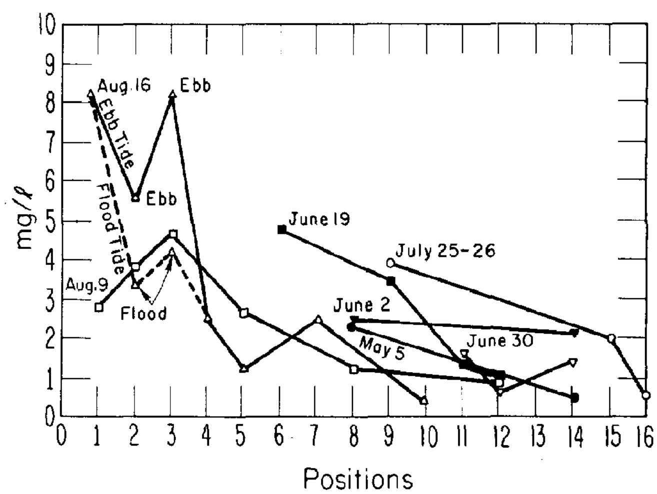


Figure 32. Total suspended solids plotted against relative distance from the harbor.

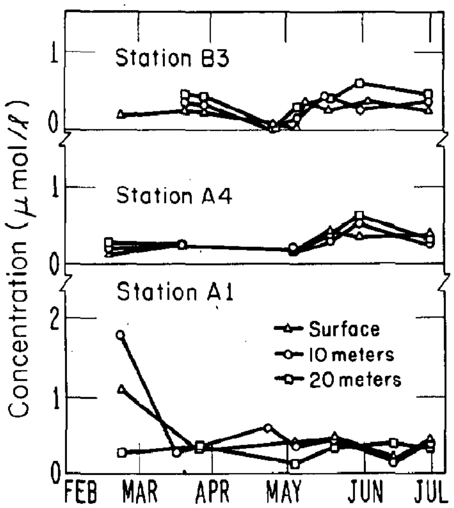


Figure 33. NO_2^- *concentrations as a function of time for stations A1, A4, and B3.*

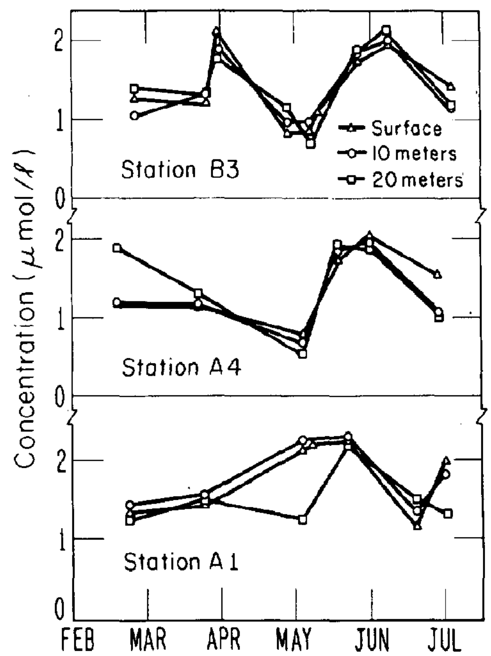


Figure 34. $PO_4^{\equiv}$ *concentrations as a function of time for stations A1, A4, and B3.*

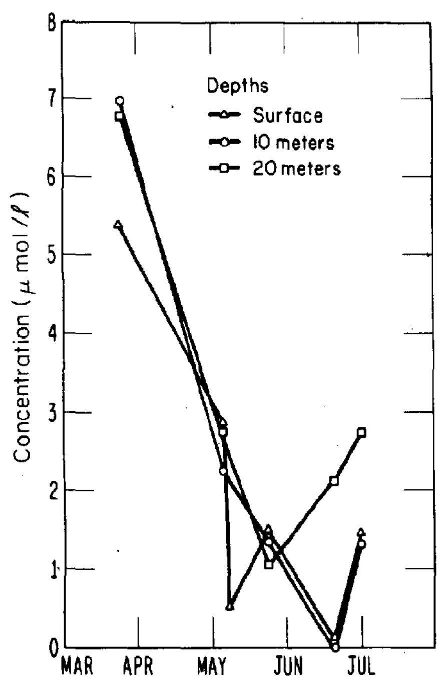


Figure 35. NO_3^- *concentrations as a function of time for station A1.*

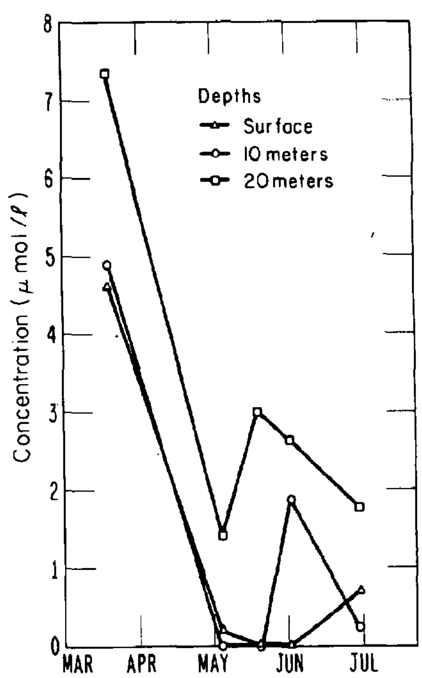


Figure 36. NO_3^- *concentrations as a function of time for station A4.*

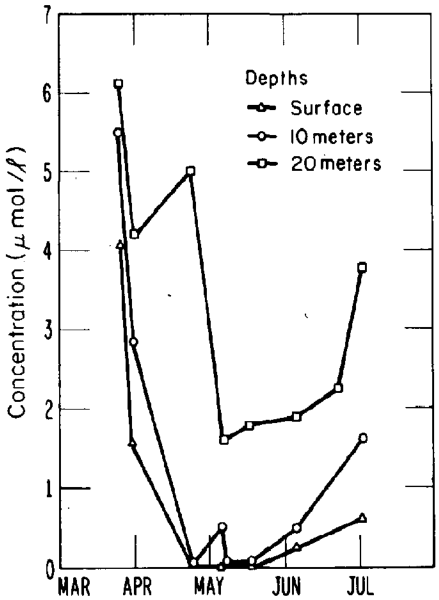


Figure 37. NO_3^- concentrations as a function of time for dredge site B3.

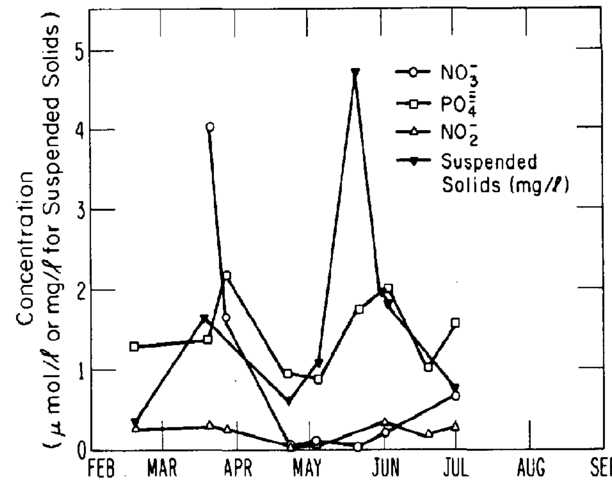


Figure 38. Concentrations of selected nutrients and total suspended solids as a function of time for station B3.

4.3.3 Discussion

Phosphate-phosphorus is present in excess even in the bloom season. Since nitrate-nitrogen is reduced to undetectable levels, there is a possibility that nitrogen is the limiting element. Analyses of ammonia-nitrogen are necessary to confirm this hypothesis. In any case, it can be seen that further addition of phosphate-phosphorus is not the critical polluting factor leading either to increase of algal growth or to eutrophication.

4.4 Physical Oceanography

The main reason for studies of the physical oceanographic characteristics of the NOMES area was the need to relate water mass movements to phytoplankton and water chemistry sampling. Light penetration measurements were made to assist in interpretation of phytoplankton samples. Dispersion studies were conducted in order to assist in predicting the time-space fate of the discharge plume to be created during test mining. Project activities included a survey of the literature on the physical oceanography of Massachusetts Bay (Bumpus, 1974) and field studies, which are discussed below.

The literature survey revealed that, prior to NOMES, no concerted effort had been undertaken to study Massachusetts Bay, per se, or any part thereof. Nevertheless, enough data were available to describe the annual temperature-salinity cycle with a fair degree of certainty. Bumpus also reported a general understanding of the advance and retreat of the tidal oscillation and of the residual drift.

Massachusetts Bay lies on the west side of the Gulf of Maine in the vicinity of 42° N., 70° W. (fig. 10). It is bounded on the north by Cape Ann, on the west by the eastern coast of Massachusetts (centered on Boston), and on the south by Cape Cod Bay and Cape Cod. Land constitutes 75% of the perimeter of the combined Massachusetts and Cape Cod Bays. The chief topographic feature is the submarine ridge that rises to within 20 m of the sea surface on the east side of the Bay between Cape Ann and Cape Cod. Two channels, one south of Cape Ann (60 m) and one north of Cape Cod (60 m grading to 40 m), separate Stellwagen Bank from the mainland. This submarine ridge blocks the free exchange of water at depth with the Gulf of Maine and is important in triggering the internal waves in the seasonal thermocline. The water deepens west of Stellwagen Bank to Stellwagen Basin, to 80 m or more. Then, toward the coast, the bottom gently rises again. East of Boston and Plymouth the bottom is hummocky and rough, whereas it is generally smooth in Cape Cod Bay, Stellwagen Basin, and on Stellwagen Bank.

4.4.1 Temperature

The annual cycle of temperature is demonstrated in the temperature-time-depth profiles for Boston Lightship from 1956 to 1970 (figs. 39 and 40). The lightship was located at 42°20.4' N., 70°45.5' W., quite near the mine-test site shown in figure 12.

During January the temperature approaches a minimum, with temperatures ranging from 1° to 6°C. The colder temperatures occur in Cape Cod Bay, the warmer ones east of Stellwagen Bank. No vertical stratification occurs in the upper 40 m. Minor stratification, <1°C, occurs below that level.

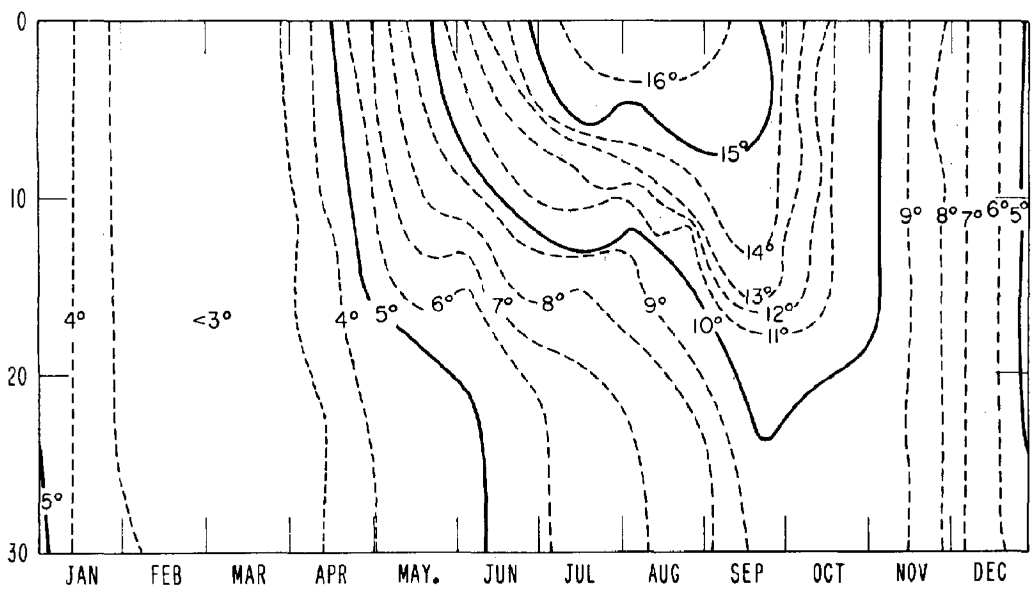


Figure 39. Depth profiles of mean annual temperature cycle (°C) at Boston Lightship, 1956 to 1970.

The temperature minimum, 0° to 3°C, is reached in February with the lowest temperature occurring in Cape Cod Bay. The water is virtually isothermal vertically, the gradient being <1°C.

By March, vernal warming has commenced with temperatures ranging from 2° to 5°C. As before, the colder temperatures are found in Cape Cod Bay and the warmer ones east of Stellwagen Bank. Vertical temperature gradients are <1°C.

Vernal warming progresses in April to the stage where a vertical temperature gradient of nearly 2°C is apparent over most of Massachusetts Bay. Surface temperatures range from 4° to 6°C, whereas bottom temperatures are restricted to 2° to 4°C. Warmest temperatures occur in the shallow parts of Cape Cod Bay and the coldest near the bottom on the east side of Stellwagen Bank.

By May the bottom temperature has warmed very little to <4°C, except in the shallow parts of Cape Cod Bay, where it reaches 10°C. On the other hand, surface temperature has risen to >9°C for the most part, reaching 12°C in isolated patches. The diffuse vertical gradient is restricted to the upper 30 m.

In June the deeper parts of Massachusetts Bay are still <4°C. Temperatures in the vicinity of 40 m may approach 8°C, or even 11°C on the east side of Cape Cod Bay. Surface temperatures range between 13° and 17°C. The vertical temperature gradient is chiefly confined to the upper 40 m.

Bottom temperature continues with little change into July. Surface temperature east of Boston and over Stellwagen Bank approaches 15°C, whereas over Cape Cod Bay it approaches 19°C, and east of the southern part of Stellwagen Bank it reaches 23°C. The thermocline of several degrees per meter centered about 10 m lies below a much weaker gradient.

By August the bottom temperature is still isolated from the annual warming cycle. Bottom temperatures below 40 m remain well below 10°C.

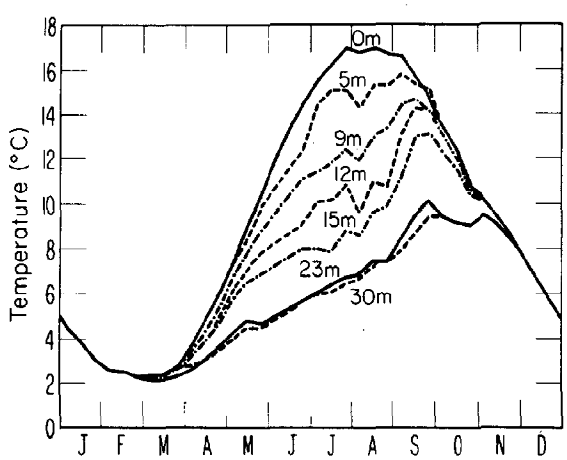


Figure 40. Annual cycle of mean temperature at standard levels below sea surface, Boston Lightship, 1956 to 1970.

Surface temperatures approach 20°C. The mixed surface layer has deepened to below 10 m over much of the area, and the thermocline has been pressed down to between 15 and 25 m.

Surface temperatures commence to cool appreciably in September, ranging from 12° to 16°C throughout Massachusetts and Cape Cod Bays. Bottom temperatures continue to approximate 6°C in the deeper parts. The thermocline continues to deepen, centered near 20 m, and continues to become more diffuse.

By October the surface temperature is reduced to about 14°C and the deep bottom temperature has increased a degree or so to 7° or 8°C as the thermocline becomes more diffuse and deepens. The mixed surface layer may extend from the surface to 10 to 20 m.

The autumn overturn is in full force during November. The water is virtually isothermal with depth at 8° to 11°C.

During December the overturn continues as the whole water column cools to about 7°C.

The whole water column is thoroughly mixed until the end of March when a very weak vertical gradient commences as the surface begins to warm. This heat is mixed downward quite effectively to about 15 m through May, following which the thermocline strengthens between 5 and 15 m through August. In the meantime, the bottom waters are warming very slowly at a rate of about 1°C per month. Maximum surface temperature is reached in August. Very slight cooling occurs in September. During this month heat is mixed downward so that the strongest part of the thermocline is centered at about 15 m, and the maximum bottom temperature is achieved by the end of September. Temperature drops rapidly during October so that by early November the whole water column is isothermal again and is chilling at a rate of about 3°C per month.

The data suggest, in addition to the cycle outlined above, secular differences from year to year as to the maximum or minimum temperatures reached, the times of maximum or minimum, and the effect of irregular upwellings of cold water that penetrate the underside of the thermocline in July and August.

Water temperatures observed during phytoplankton sampling agreed with the trends discussed above. Figure 41 compares 1973 data at station B3 with 1956-1970 data at the nearby Boston Lightship.

Figure 42 shows 1973 temperature data from five other stations: A2, A4, B3, C2, and C4 (see fig. 12 for locations). The temperature range over the year was from 0° to 18.8°C. From December to March, temperatures were near the lower part of the range (0° to 5°C). Profiles were essentially homogeneous indicating typical winter conditions characterized by vertical mixing. In April, the situation began to change with the warming of the surface waters and, eventually, the development of a marked thermocline. Stratification increased, and by midsummer three layers were well defined: surface

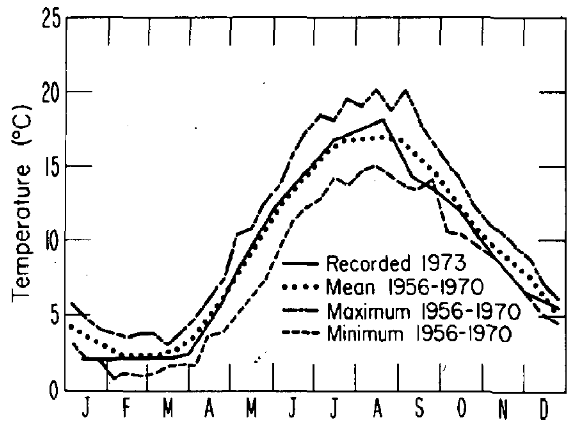


Figure 41. Maximum, minimum, and mean surface water temperatures recorded at Boston Lightship from 1956 to 1970, compared with surface temperatures recorded at station B3 in 1973.

layer to about 10 m, temperatures between 12° and 17°C; 10 to 20 m, temperatures between 8° and 9°C; 20 m to the bottom, temperatures between 5° and 6°C. By September the "surface" layer extended down to 15 m. October through December 1973 saw the coming of winter conditions causing cooling of the surface layer, reduction of the three-layered system to two and, eventually, vertical homogeneity. Station C2 does not clearly show a three-layered system because of the shallower depth. Also, because the station is closer to shore, there is more fresh water at C2; thus in January the water there was below 1°C at the surface. Detailed temperature data from the phytoplankton cruises are offered by Frankel and Pearce (1973).

4.4.2 Salinity

The amount of data on salinity distribution in Massachusetts Bay is minimal. Except for 1956-1970 data for the Boston Lightship station, surface salinity data are available for only March, April, May, June, September, October, and December. Fewer data are available at depth.

The salinity at the surface ranges between 30°/₀₀ and 33°/₀₀, with the minimum occurring in May and the maximum in March. In general the surface isohalines, during any month, trend north and south with salinity increasing offshore except in May when the lowest salinity appears to lie between Cape Ann and Provincetown. This is probably the result of the Merrimack spring runoff drifting southward across the middle of the Bay. Except in May, Cape Cod Bay tends to be fresher than the rest of Massachusetts Bay but only by a fraction of salinity.

The annual salinity cycles at Boston Lightship shown in figure 43 include the surface maximum, mean, and minimum decadal values for the period 1956-1970 as well as the mean monthly bottom values. The mean range varies from 30.7°/₀₀ to 32.4°/₀₀, with the maximum during January and February, and the minimum in May, followed by a gradual, virtually linear return to the January maximum. Extreme salinity values range from about 28°/₀₀ to nearly 33°/₀₀.

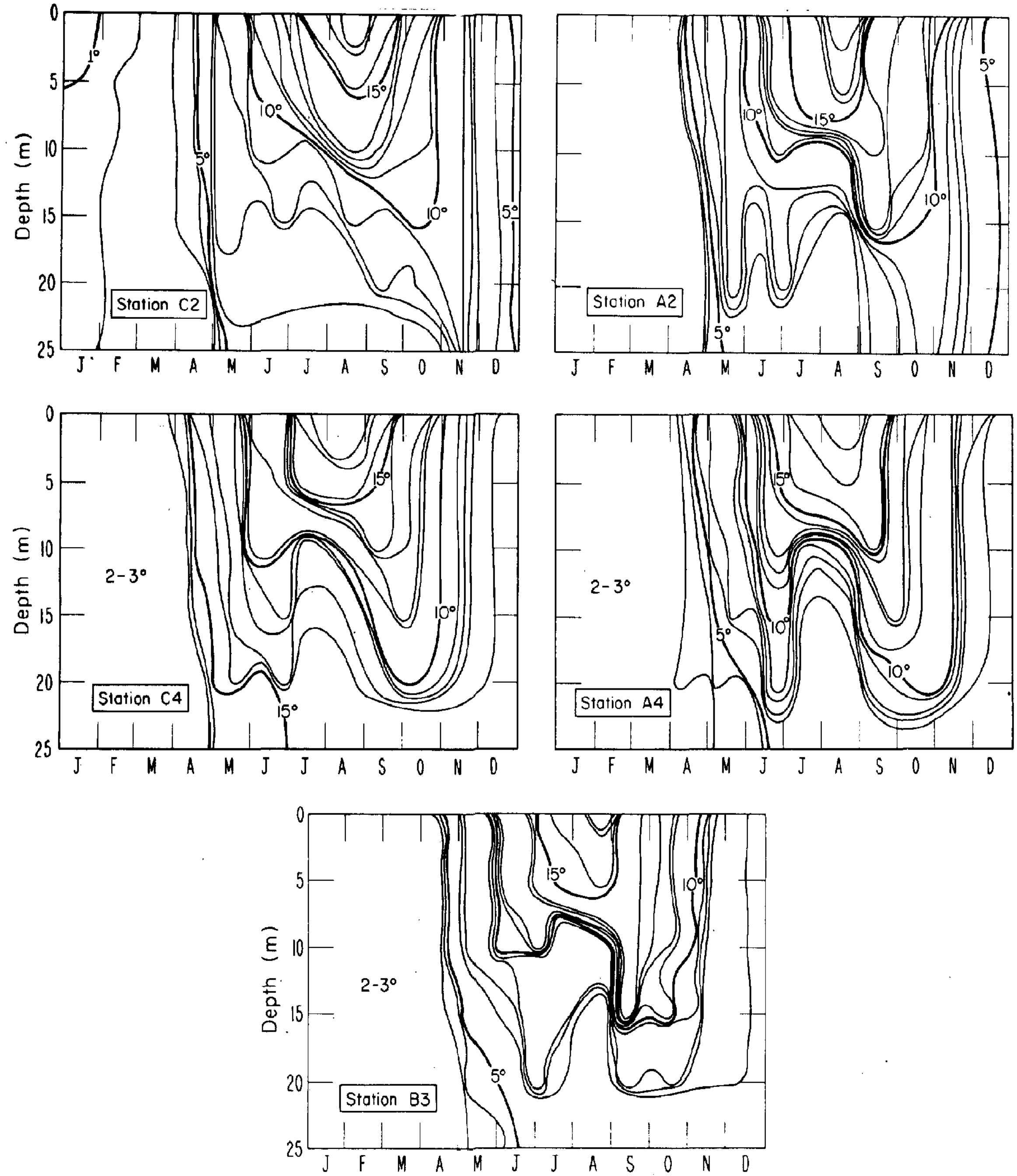


Figure 42. Temperature profiles (°C) during 1973.

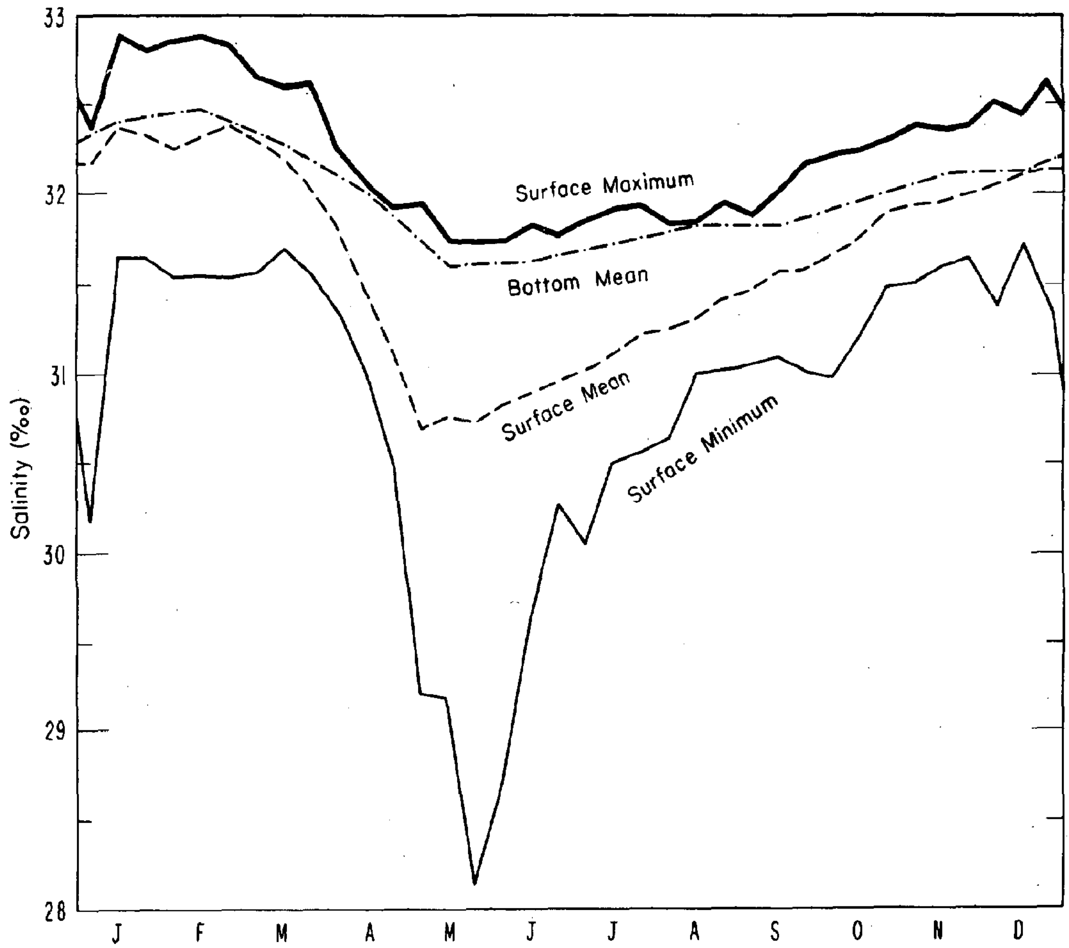


Figure 43. Annual cycle of salinity at Boston Lightship, 1956-1970.

The mean bottom salinity ranges from 31.6°/₀₀ to 32.5°/₀₀. For half the year, October to March, the average difference between the surface and bottom salinity is 0.2°/₀₀ or less. This substantiates the indication of temperature data that the water column is well mixed during this period. The minimum salinity is observed at all depths in May as a direct result of the spring runoff.

Figure 44 combines the average temperature and salinity information at Boston Lightship for 1956 to 1970. The diagram reiterates the warming cycle that commences in March, continues to August at the surface and to October at the bottom, and then commences to chill back to the February condition. The salinity cycle is at a maximum during the coldest period, freshens throughout the water column to a minimum in May in response to the runoff cycle, and gradually, through mixing and advection, returns to the winter maximum.

Salinity observations made in conjunction with phytoplankton sampling show a salinity range for the year of 28.6°/₀₀ to 33.0°/₀₀ at the surface

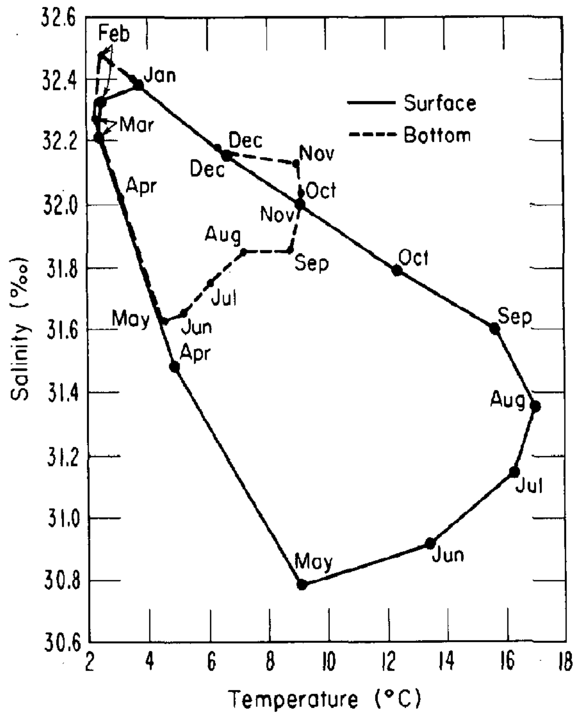


Figure 44, Annual cycle of temperature-salinity relationship at Boston Lightship, 1956-1970.

(Table 29; fig. 45). The low value occurred on May 5, 1973, the high value on September 29, 1973. From December to March, values averaged about 30.2°/oo to 31.2°/oo. The water column appeared well mixed; no vertical stratification was evident during this period. Salinity values were higher with distance from shore. After March, salinity values decreased from spring runoff. Seasonal climatological conditions also brought about the initiation of vertical heterogeneity. Lowest values of the year occurred during the spring from April to June coincident with peak runoff conditions. From July to September, values increased again to between 30°/oo and 33°/oo. Vertical stratification continued until around mid-December. December 22 data were the first to show homogeneous salinity profiles, which were caused by mixing.

4.4.3 Currents and Dispersion

The currents in coastal waters may be classed by their time scales, for instance, mean currents, tidal currents, and higher frequency currents associated with turbulence and waves. The most obvious are the tidal currents, frequently modified by the wind. Less obvious are the mean or residual currents, and least recognizable and only recently observed in this area are the high-frequency phenomena.

The semidiurnal tidal oscillation into Massachusetts Bay results in a mean tidal rise and fall of about 3 m. Spring ranges are about 0.5 m greater. The flood current sets westward into Massachusetts Bay, the ebb northeastward to eastward. The velocity at strength over Stellwagen Bank increases from about 0.4 km/hr at the northern end to about 2 km/hr at the southern end. The tidal current at Boston Lightship is weak, averaging less than 0.4 km/hr at strength. The velocity and direction of the current there is greatly influenced by the wind.

Table 29. Salinity Profiles in Massachusetts Bay

Station/ Depth		Salinity (°/₀₀) 1972 12/19	1973 1/13	2/1	2/10	3/21	3/31	4/23	5/5	5/19	9/10	9/29	10/13	12/1	12/22
A2	Surf.	30.5	30.9	31.2	30.5	30.7	29.8	29.1	29.3	29.3	31.9	32.1	32.1	28.6	*
	5m	"	"	"	30.4	"	30.1	29.2	29.0	"	"	32.2	"	29.1	
	10m	"	31.0	"	30.2	"	30.6	29.8	29.1	"	"	"	32.3	26.6	
	15m	"	"	"	30.1	"	"	30.2	29.5	"	31.8	32.0	32.5	"	
	20m	"	"	31.1	30.5	"	"	30.6	29.6	"	32.4	32.7	32.8	"	
	25m	-	-	-	-	-	-	"	29.8	29.8	-	-	-	-	
A4	Surf.	30.8	31.0	31.2	30.7	30.7	29.9	29.1	29.0	29.3	31.8	31.8	32.3	24.1	*
	5m	"	"	"	"	"	30.0	"	"	"	32.0	32.2	32.4	24.8	
	10m	"	"	"	30.8	"	30.1	29.4	29.2	"	"	32.3	32.3	"	
	15m	"	"	31.3	30.9	"	"	29.8	29.4	"	31.8	32.2	32.4	"	
	20m	"	"	"	-	"	30.3	30.1	29.9	29.9	32.6	32.6	32.8	"	
	25m	-	-	-	-	-	-	30.4	30.2	30.2	-	-	-	-	
B3	Surf.	30.3	30.6	31.3	31.1	30.7	30.0	29.3	29.2	*	31.6	32.0	32.2	32.5	30.7
	5m	"	"	"	31.0	"	"	29.4	"		31.9	32.1	32.4	30.0	"
	10m	"	"	"	"	"	30.3	"	"		"	"	"	31.5	30.2
	15m	"	"	31.2	"	"	"	29.5	"		"	32.5	32.3	31.9	30.6
	20m	"	"	"	"	"	"	30.3	29.9		32.1	32.8	32.9	"	"
	25m	-	-	-	-	-	-	30.6	30.2		-	-	-	-	"
C2	Surf.	29.8	29.7	30.8	29.8	30.2	29.5	29.1	29.2	29.0	31.4	32.0	31.9	33.1	*
	5m	"	30.2	"	30.4	"	"	29.2	"	"	31.5	31.9	32.2	"	
	10m	30.0	30.3	30.9	"	30.6	29.8	29.4	"	"	31.6	32.1	32.2	"	
	15m	30.1	30.6	"	30.2	"	"	30.0	"	29.1	32.1	32.3	32.3	"	
	20m	30.2	"	-	30.4	"	30.1	30.2	29.5	29.6	32.2	32.8	32.9	-	
	25m	-	-	-	-	-	-	"	-	29.8	-	-	-	-	
C4	Surf.	30.3	30.9	31.3	30.9	30.7	29.8	29.4	29.0	29.2	31.9	32.4	32.1	31.9	*
	5m	30.4	"	"	31.0	"	30.4	29.5	"	"	31.7	32.3	32.4	"	
	10m	"	"	"	"	"	30.1	"	29.2	"	32.1	32.2	32.3	32.2	
	15m	30.6	"	"	30.9	"	"	29.6	29.4	"	32.2	32.4	"	"	
	20m	"	"	"	30.8	"	"	30.1	"	29.5	32.5	32.6	32.4	"	
	25m	-	-	-	-	-	-	30.3	29.7	29.9	-	-	-	-	

* No data collected.
\- No reading at that depth

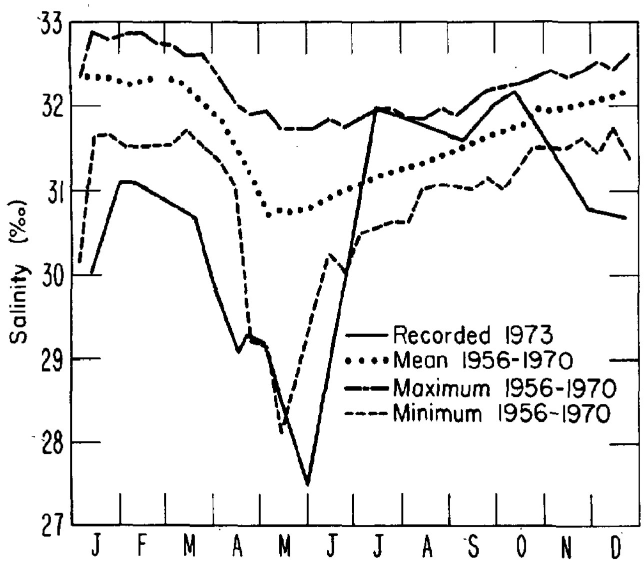


Figure 45. Maximum, minimum, and mean surface salinity values recorded at Boston Lightship from 1956 to 1970, compared with surface salinity values recorded at station B3 in 1973.

For some distance northwestward of Cape Cod the tidal currents have a slight set into Cape Cod Bay on the flood and out of the Bay on the ebb. Along the north shore of Massachusetts Bay the flood sets in a generally southwesterly direction and the ebb northeasterly. The speeds of the tidal currents are on the order of 0.9 km/hr or less and as remarked above are greatly influenced by the force and direction of the wind. The flood sets westward, the ebb eastward off the entrance to Boston Harbor, increasing to over about 2 km/hr as the entrance is approached.

Tidal currents have been measured 1 m above the bottom in various parts of Massachusetts Bay. Maximum current speeds (26 to 29 cm/sec) in the deep basin west of Stellwagen Bank were lower than those over the bank (32 to 47 cm/sec) or inshore off Marblehead (43 cm/sec). Thus near-bottom current speeds appear to be strongest in the outer part of the Bay including the channel between Cape Cod and Stellwagen Bank, weaker near shore, and weakest in the deep basin. Divers sampling the benthos during this project reported occasional encounters with bottom currents strong enough to interfere with sampling. It is probable that these currents were about 2 km/hr.

The residual drifts are inferred from drift bottle and seabed drifter data. Massachusetts Bay lies on the western side of the cyclonic Gulf of Maine eddy. This Gulf of Maine eddy provides a southward flow across the mouth of Massachusetts Bay, achieving its fastest drifts during April and May. The surface drift is thus southward at speeds of 1.8 to 9 km/day east of Stellwagen Bank. West of Stellwagen Bank the drift tends to follow the coastline, i.e., southward south of Cape Ann into Massachusetts Bay, southward past Boston Harbor, thence cyclonically around Cape Cod Bay and northeastward past Race Point.

Bottom residual drifts are an order of magnitude slower than the surface drifts, i.e., 0.4 to 0.9 km/day. In general, these drifts are southward to southeastward across Stellwagen Bank and in the deeper waters to the east of the bank, and southward to southwestward (i.e., with a shoreward component) over the inner part of Massachusetts Bay. The southerly drift in Massachusetts Bay extends into Cape Cod Bay.

Recent studies west of Stellwagen Bank indicate that the seasonal thermocline is subjected to a 6- to 8-min oscillation for about 2.5 hr during the tidal flood. Maximum vertical displacement of the internal wave occurs at a depth of 20 m. Long-crested, short-wavelength narrow surface bands, parallel with the sill, propagating westward, were measured concurrently with the high-frequency temperature oscillations. Some 9% of the tidal energy appears to be converted into semidiurnal internal waves in summer occasioned by the sweep of the incoming tide over Stellwagen Bank when the seasonal thermocline is just above the sill depth of the bank.

Drogues and dye survey

A preliminary survey of current directions, velocities, and dispersion rates was conducted for one tidal cycle over 2 days in late July 1972 (Coastal Research Corp., 1972). Rhodamine dye was introduced and then tracked by boat and air over a 6-hr period on each of 2 days. Altogether, 18 drogues were deployed, nine at 1.5-m depth and nine at 9 m. Figures 46 and 47 record dye advection and diffusion near the mine site for ebb tide and flood tide.

Figures 48 and 49 depict drogue movements and velocities at the 1.5-m and 9-m levels during the same tidal episodes. Average velocities of 26 cm/s for the 1.5-m drogues and 12 cm/s for the 9-m drogues were calculated. The dye traveled in the same direction and roughly at the same velocity as the 1.4-m drogues for both ebb and flood tides. The average dispersal rate was 10 m^2/s for the ebb tide and 3.4 m^2/s for the flood tide.

The currents in the area of the proposed mining site exhibited a marked southerly direction in the initial stages of both flood and ebb tides. For the flood tide the 1.5-m drogues traveled in a southeast direction with an average velocity of 27 m/s while the 9-m drogues traveled in a southwest direction with an average velocity of 11 m/s. For the ebb tide both sets of drogues started out at an almost due south heading until the 1.5-m drogues shifted to a westerly and then to a northwesterly heading. At the same time the 9-m drogues shifted to an easterly and then a northeasterly heading.

Test particle dispersion experiment

This experiment was conducted in Massachusetts Bay in June 1973, 1 year prior to the planned experimental mining, in order to develop a technique to predict where a discharge plume would travel in response to prevailing currents and winds. The experiment has been reported in detail (Hess and Nelson, 1975; Nelson et al., 1977; Mayer, 1975); thus only a summary is included here.

In brief, 2700 kg of small ($0.5 < d < 50$ μm) particles were released to the water surface at the mine site in the form of a slurry simulating somewhat the overflow of a hydraulic dredge. The movement of the resultant plume was traced by drogues for 10 days and sampled for temporal and spatial distributions of particles. These (Eulerian) measurements were augmented by 1 month of moored current meter (Lagrangian) measurements at three levels in the water column at seven stations. The current meter records began 2½ weeks

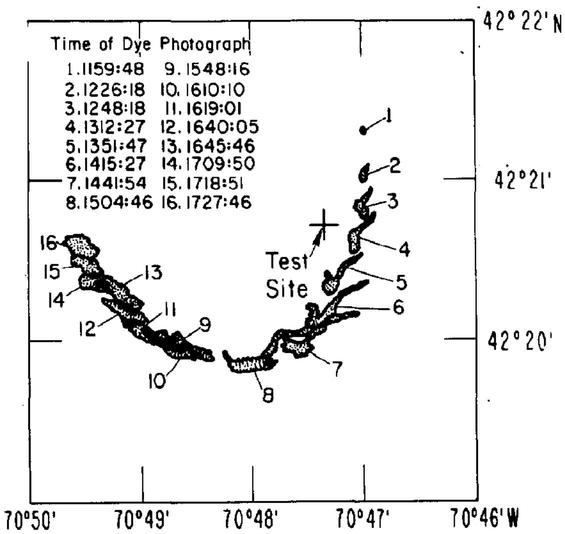


Figure 46. Dye movement near test site during ebb tide, July 27, 1972.

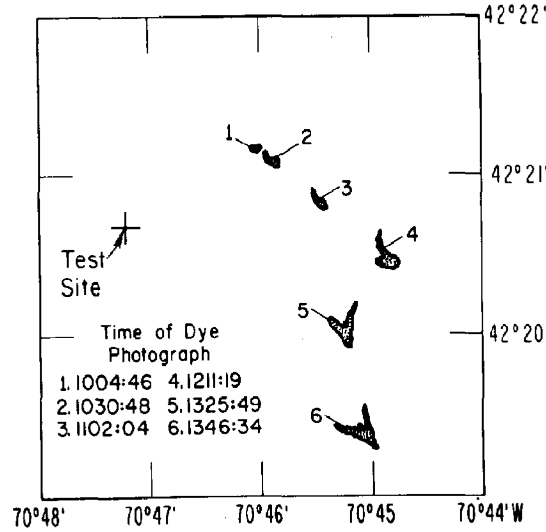


Figure 47. Dye movement near test site during flood tide, July 31, 1972.

before the release of the tracer particles and continued through the experiment. Salinity, temperature, and wind observations also were taken during the experiment.

During the month, a strong north-south current shear zone was observed. The mean motions within 10 km of shore were predominantly northward; beyond that, the motions were exactly southward.

The histograms of current-meter data in polar form (fig. 50) display the preferred directions of the water motion as the frequency distribution of currents, partitioned into 10° increments, where the length of each line represents the percentage of the total record length occupying that direction segment. Frequency distributions change significantly with depth. Level 1 has fairly homogeneous distributions of currents, except at station 1. Levels 2 and 3 show that materials would be transported in a preferred southwest and northeast direction. Of course, there is no phase information contained in these roses. This means that material introduced into the water column at the same place, but at different times in the tidal cycle, could be transported in completely opposite directions.

Tracks of the 7- and 12-m-depth drogues are shown in figures 51 and 52. The tracks were found to be in agreement with the current meter observations. It appears that the east-west tidal motion transported the drogues to the east, through a sharp shear zone, into a southerly flowing current regime where they remained. Conceivably this could have occurred quite differently. If the drogues had been deployed at a different time, they probably would have gone much farther north before turning south.

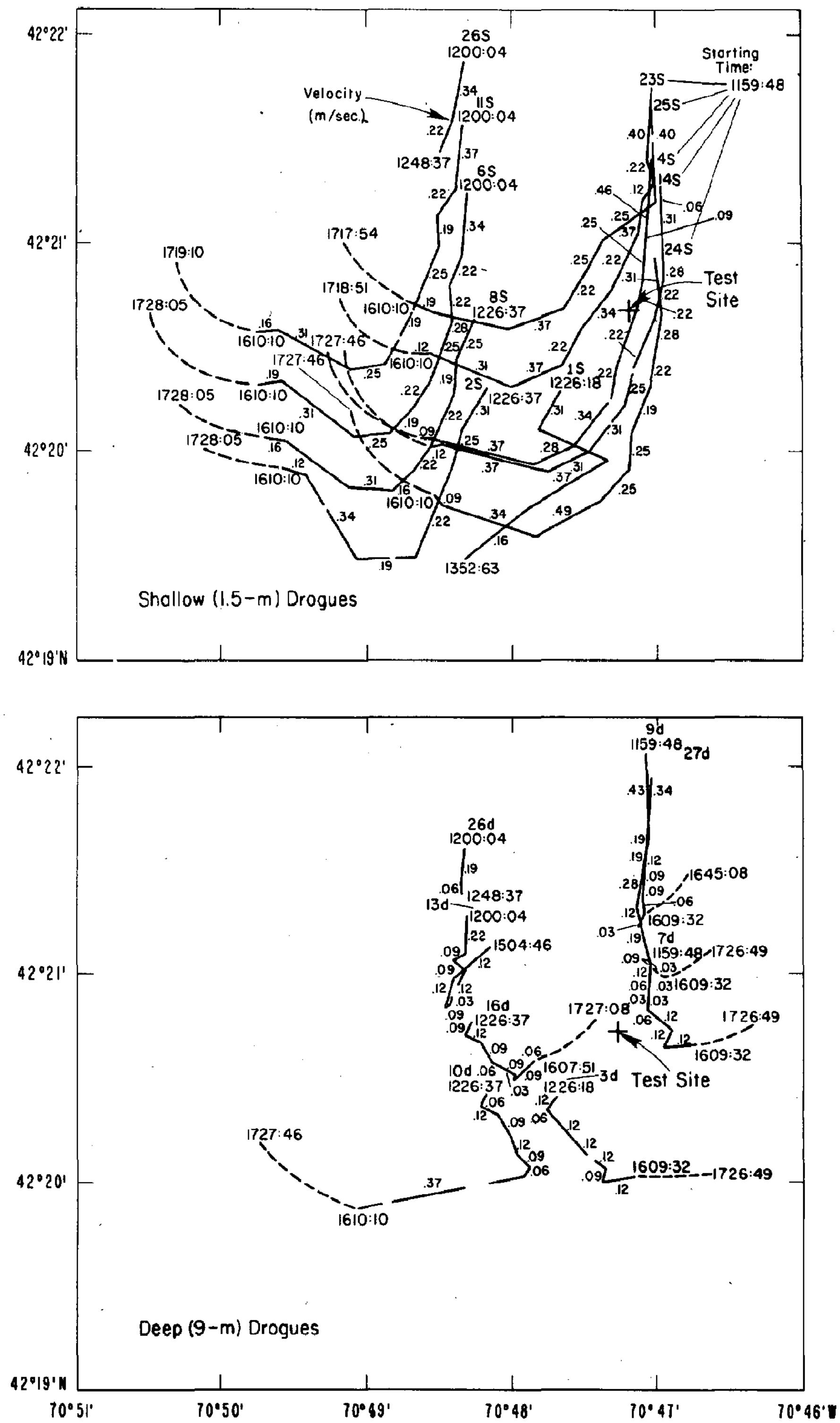


Figure 48. Drogue movements and velocities near test site during ebb tide, July 27, 1972.

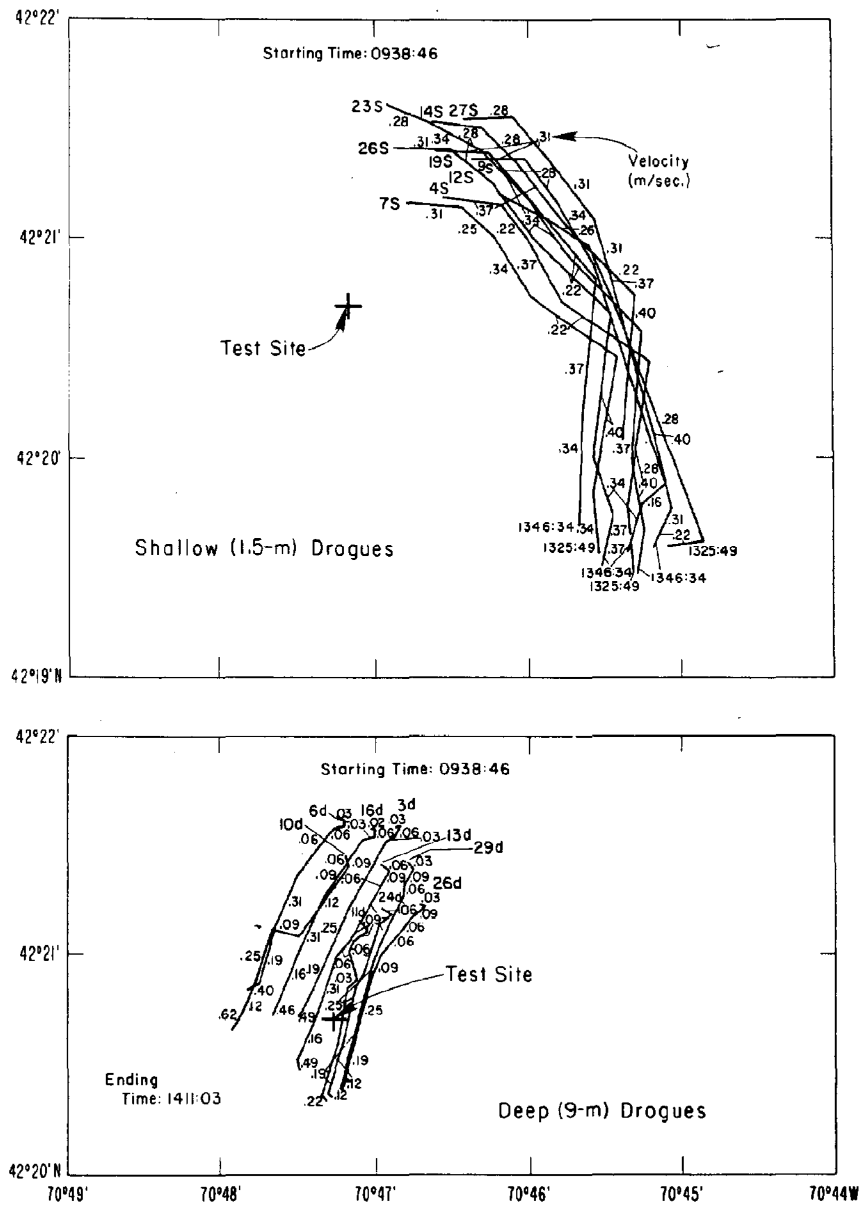


Figure 49. Drogue movements and velocities near test site during ebb tide, July 31, 1972.

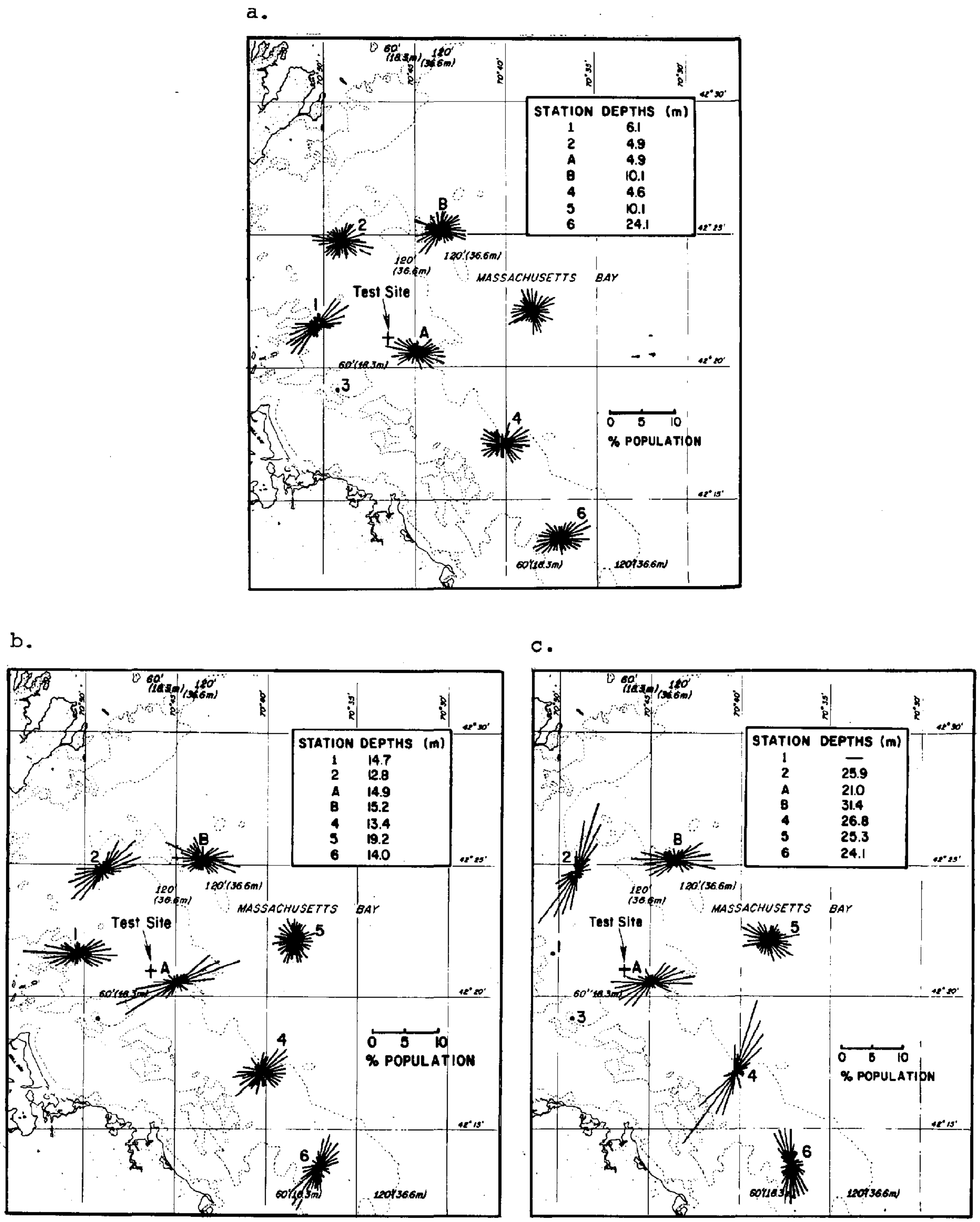


Figure 50. Water current direction roses for current meters in Massachusetts Bay. Depth contours are given in feet and meters. a-Upper-level meters; b-Middle-level meters; c-Lower-level meters.

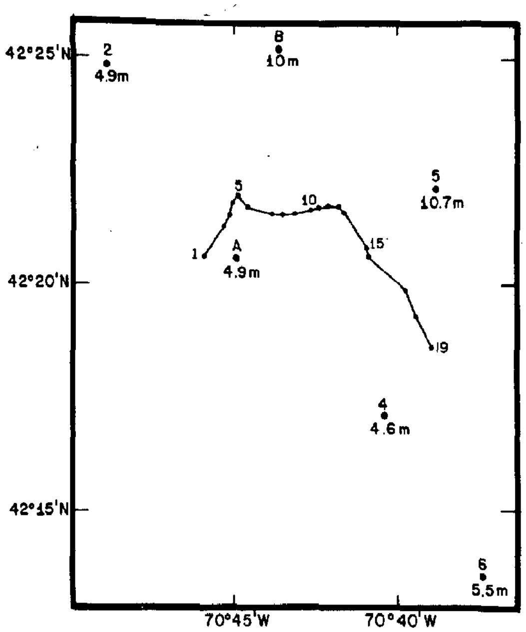


Figure 51. Seven-m drogue track from 1100, June 11, to 1600, June 12. 19-1 through 19-19 are current vectors at the time of drogue position observations.

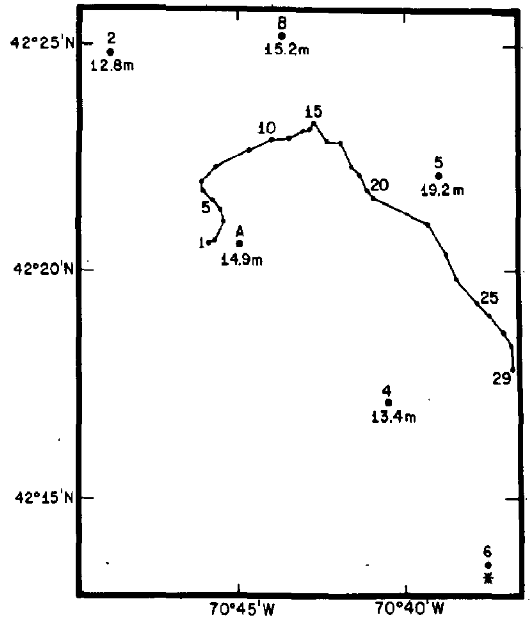


Figure 52. Twelve-m drogue track from 1100, June 11, to 0600, June 13. 20-1 through 20-29 are current vectors at the time of drogue position observations.

Two types of particles were used as tracers. The first type was small spherical glass beads such as those used in night reflectors on highways. These were selected because the density of these particles is 2.5 g/cm^3, approximately that of quartz (2.64 g/cm^3) and sand. Nine hundred kilograms of glass beads were used in the experiment. With an average particle size of 13.8 μ. an estimated 2.6 x 10^{14} glass beads were introduced into the water column.

As a supplementary tracer, laboratory-grown sphalerite (ZnS) crystals with fluorescent inclusions also were used (ZnS; Hellecon 2210, U.S. Radium Corp.; P-22 Green, GTE Sylvania Corp.). Their fluorescent property makes them easily identifiable under a microscope in ultraviolet light. Four hundred and fifty kilograms of sphalerite crystals were used in the experiment. Since the density of sphalerite (4.1 g/cm^3) is greater than that of glass beads (2.5 g/cm^3), a finer distribution of these was chosen so that the hydraulic settling characteristics of the two types of particles would be roughly equivalent. With an average particle diameter of 2.8 μ, an estimated 3.8 x 10^{15} particles of sphalerite were used in the experiment. Table 30 tabulates particle size distribution for both particles.

The filter pads from the shore-based laboratory were delivered to an independent commercial laboratory that had counting equipment utilizing image analysis by computer. For reasons not clearly understood, the final glass-bead data delivered by that lab were entirely inaccurate and could not be

Table 30. Tracer Particle Size Distributions

Small Sphalerite			Large Sphalerite			Glass Beads		
Mean Diameter (μ)	%	WT %	Mean Diameter (μ)	%	WT %	Mean Diameter (μ)	%	WT %
1.15	9.4	0.18	3.5	0.6	0.002	3.0	0.5	0.0
1.43	4.9	0.18	4.5	1.5	0.013	5.0	4.55	0.04
1.8	0.8	0.72	5.7	13.0	0.22	8.0	17.15	0.62
2.25	13.8	1.98	7.2	0.0	0.0	12.0	24.20	2.94
2.85	17.3	5.05	9.0	8.4	0.56	16.0	13.65	3.94
3.6	16.6	9.73	11.3	9.6	1.27	20.0	16.20	9.10
4.5	13.5	16.32	14.4	8.6	2.36	25.0	7.0	7.70
5.65	8.3	18.74	18.0	11.9	6.39	30.0	5.0	9.46
7.15	4.3	19.46	22.7	22.0	23.7	36.0	3.5	11.5
9.0	1.7	16.50	28.7	20.4	44.4	45.0	6.5	28.2
11.35	0.5	9.01	>32.0	7.0	21.1	50.0	1.5	13.2
14.35	0.1	2.52						
18.0	-	0.90						
>25.0	-	0.72						

used. The final analysis is based on data from the sphalerite counts made in the shore laboratory and on board the tracking vessel. The daily sphalerite counts are plotted in sequence of successive days and depths (figs. 53-55).

On D-day (particle-dump day) all samples were obtained by pumping from the various depths. Later it was discovered that sphalerite particles adhered to the pump hose walls and therefore no sphalerite data were plotted for D-day.

Figure 53 shows the sphalerite dispersion on day D+1. The 5-m plot shows little dispersion northward, but high concentrations moving eastward from the dumpsite. The 10-m cloud seems to be broken into two major sections, one with a high of 11640 particles/ℓ and the other with a high of 21175 particles/ℓ. It is interesting to note that the former high has drifted northward in a direction compatible with the 7-m current vectors of station A. The major high of 21175 particles/ℓ is roughly in the same position as the 7-m drogue at that time. The 15- and 20-m isopleth maps seem to exhibit the same partitioning of the plume into northwest and southeast portions. Settling is apparently taking place as evidenced by an increase in magnitude with depth of concentration highs. The general eastward motion of the higher concentrations seems to agree with the displacement of the drogues under tidally dominated eastward flow.

D+2 data found in figure 54 sustain the previous day's observation that the bead cloud has been partitioned into at least two segments. Relatively high counts increase in magnitude toward the Boston Harbor mouth at depths of 15 and 20 m. The count maximum at each datum plane is at least an order of magnitude smaller than on the previous day.

Figure 55 illustrates the plots for day D+3. On that day there were inadequate data for a plot of the 10-m level. The 5-m plot shows concentrations increasing rapidly to the south and landward, a distribution in harmony

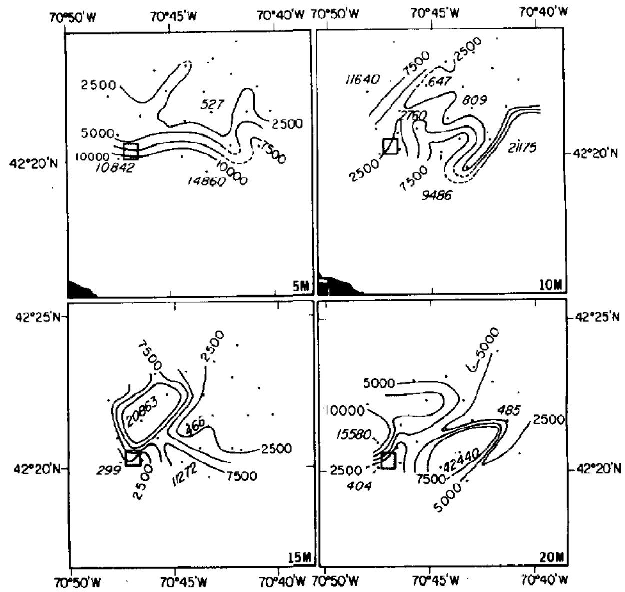


Figure 53. Sphalerite isopleth data (particles/ℓ) for day D+1. Some isopleths in high-concentration areas have been deleted for simplicity. The particle dumpsite is shown as a square.

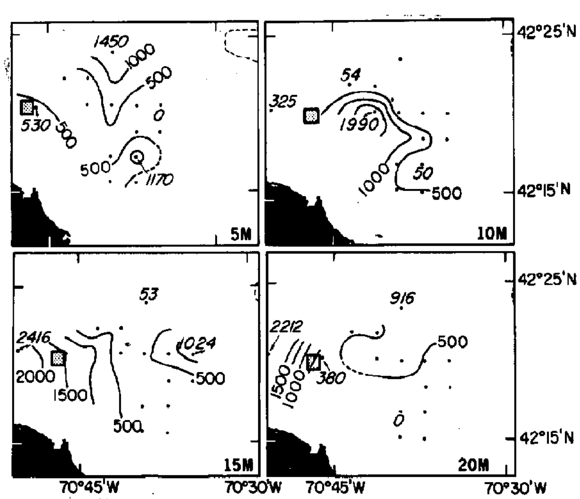


Figure 54. Sphalerite isopleth data for day D+2. The particle dumpsite is shown as a square.

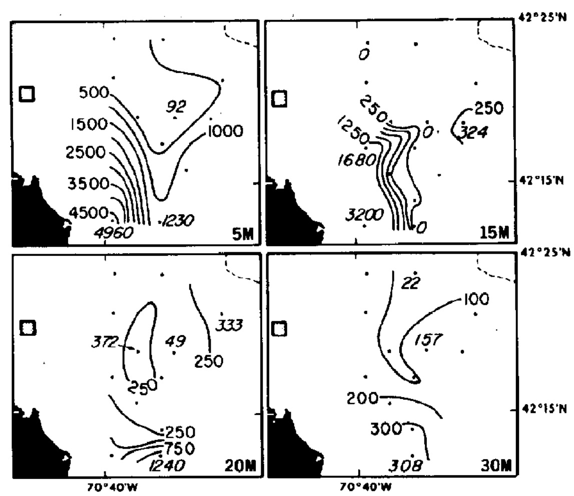


Figure 55. Sphalerite isopleth data for day D+3. The 40-m isobath of Stellwagen Bank is shown as a dashed line. Some 15-m and 20-m isopleths have been omitted for simplicity.

with the general flow of current meter stations 4 and 6 at 7 m. A similar trend is observed at 15 m in addition to a hint of plume partitioning similar to the data at 15 m for the previous day. Plots for 20 and 30 m also show partitioning with a concentration increase to the south.

On day D+4, partitioning was still evident at 5 and 10 m with relatively high values found near the dumpsite. These may be particles that started north or into Massachusetts Bay early in the experiment and then returned by current action not monitored during the experiment.

Only a partial day's work was done on D+5 because of bad weather, and the number of samples collected did not allow for a meaningful plot of the data. Day D+6 had continued bad weather and no samples were collected.

On day D+7, sampling continued from both the surface vessel and from a helicopter, which allowed a larger area to be sampled. The results of the broad helicopter coverage for surface samples showed, first, that vast areas, especially to the north, had no sphalerite particles present and, second, the concentration highs that remained were in three widely spaced groups in Massachusetts and Cape Cod Bays.

By day D+7 and after, the concentrations of sphalerite particles in the water were so low that, in using the microscope, the contamination "noise" and the count "signal" were roughly of the same magnitude. Therefore, any plots of sphalerite data would be questionable at best. However, it was possible to make Turner fluorometer measurements on days D+7 and D+8. Figure 56 is a composite of the data at 20 m. Data from 42°05' N. and to the south are for D+7; those from north of 42°05' N. are for D+8. Two noteworthy features are present in this figure. D+7 data to the south indicate a counterclockwise motion of the particles in central and southern Cape Cod Bay. D+8 data to the north show relatively high values in apparent motion to the southeast. The isopleths over Stellwagen Bank are more closely spaced, seemingly indicating a retarding influence of Stellwagen Bank on the seaward movement of water and particles.

Temperature observations show that the sphalerite concentration maximum appears at or above the base of the seasonal thermocline, and in the case of the profile with the double thermocline, a relatively high value occurs at or above each thermocline. The pre-storm conditions of this stratified two-layer system strongly suggest particles "hanging up" on or about the thermocline. This phenomenon has been observed in the world oceans at zones of rapidly increasing density (pycnoclines) and is well documented (Jerlov, 1958; Costin, 1970). Pycnoclines result from rapid changes in temperature and/or salinity with depth.

A series of mathematical modeling studies was conducted at M.I.T. under NOMES and related projects for the purpose of devloping predictive capabilities of the dispersion of solid particles in coastal waters. Both a two-dimensional finite element circulation model (Conner and Wang, 1973) and a compatible finite element dispersion model (Christodoulou and Pearce, 1975; Leimkerhler, 1974) were developed. The dispersion model was applied specifically to this experiment, and the results compared favorably (Christodoulou et al., 1976).

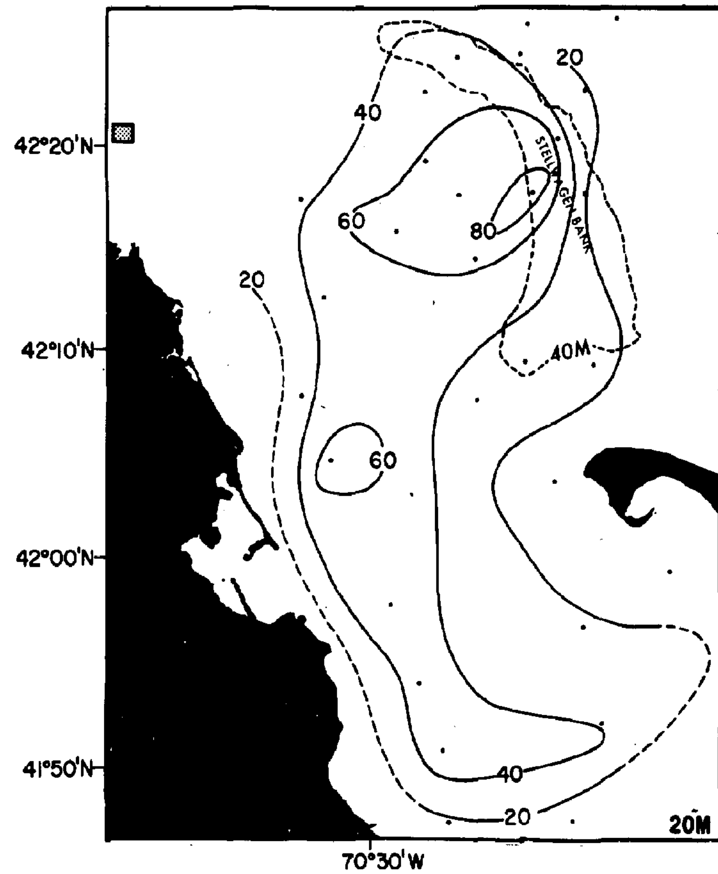


Figure 56. Composite of Turner fluorometer data for days D+7 and D+8.

When several values of dispersion coefficients are compared, 30 m^2/s appears to be closest to reality, yielding better agreement than other values (50 m^2/s and 100 m^2/s).

Although sphalerite isopleth maps indicate progressive settling with time, particle settling was apparently impeded by the presence of a strong vertical gradient of temperature and salinity (pycnocline) that existed before the storm. This pycnocline may have caused greater lateral dispersion in the upper water layer than might otherwise have been the case. Although the experimental particles may not have behaved exactly as a real dredge plume, they were a more reasonable indicator of dredge plume dispersal and behavior than dissolved dye traces, which do not exhibit the sedimentary characteristics of particles.

Caution should be used in the interpretation of the dispersal data, and conclusions should not be extended to other times of the year. From evidence presented above, it is reasonable to conclude that the dispersion of the particle plume was contingent upon the tidal cycle at introduction, the seasonal structure of the water column, and the effect of the storm, which mixed the water column down to at least 30 m in some places.

The observed dispersion of the particle plume was toward Boston Harbor (fig. 54), eastward toward Stellwagen Bank (figs. 53 and 54), and then southward along the coast into Cape Cod Bay (fig. 55) where a counterclockwise gyre was suggested (fig. 56).

4.4.4 Light Penetration

The euphotic zone is defined as that part of the water column for which there is sufficient light to support active photosynthesis. Sufficient light is considered to be 1% of that which strikes the surface. The depth of the euphotic zone was obtained by measuring with a light meter that depth at which only 1% of the surface light remains. These values were plotted for the primary stations (fig. 57).

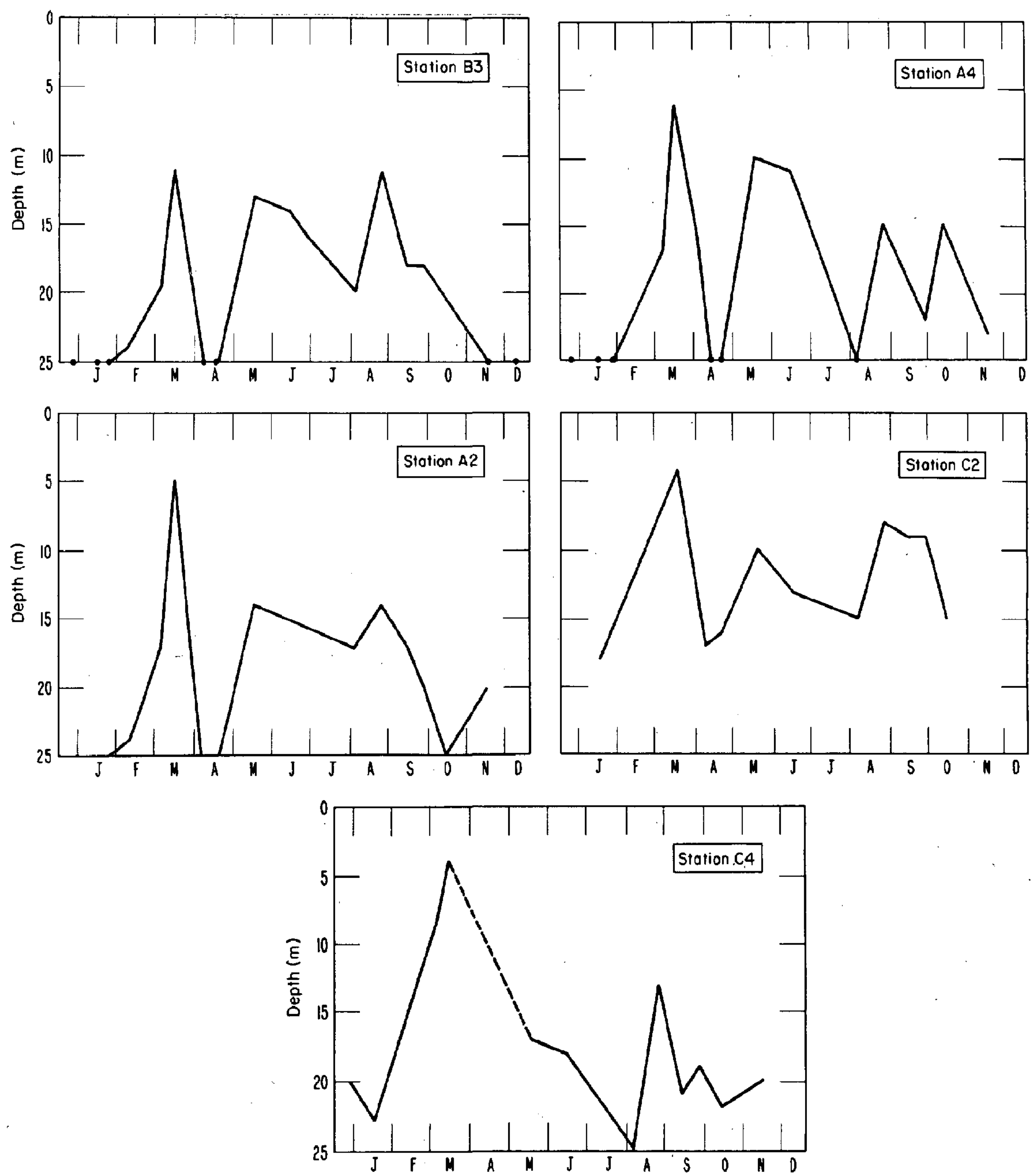


Figure 57. The depth of the euphotic zone in 1973.

At station B3, the depth of the euphotic zone ranged from 11 to 26 m (bottom) over the year. Maximum values occurred during the months of December, January, and February. By late February, spring phytoplankton and/or runoff contributed to a decrease in euphotic depth, and by March 31, a minimum was reached (11 m). Data from the two following cruises (April 28 and May 5) showed 1% of the light penetrating to the bottom. A second minimum was reached in June when the depth of the euphotic zone was only 13 m. The depth of the euphotic zone increased again more gradually with time down to 20 m in August. Then the depth decreased to a third minimum on September 10 (11 m), followed by a gradual increase in the euphotic zone to the bottom, back to winter conditions. Curves for the other stations follow this general trend. Differences in absolute depth of the euphotic zone from the other stations are functions of their location with respect to land and the depth to bottom. These factors both determined the amount of suspended sediments and phytoplankton populations. The shallowest depth of the euphotic zone recorded was 4 m at stations C2 and C4 on March 31, 1973.

5. ACKNOWLEDGMENTS

Primary gratitude goes to the principal investigators. Their names and affiliations are listed in the Preface.

Advice from the European industry was provided mainly by Dr. Roger Cloet of the Natural Environment Research Council of the United Kingdom. Description of the U.S. industrial situation relative to continental shelf sand and gravel was provided by Mr. Ed Davison of the National Sand and Gravel Association.

Special thanks also go to the following:

The Construction Aggregate Corporation for the offer of the use of its hydrobarge, at cost, for the experiment.

The Office of Sea Grant, for matching MMTC's work with related activities at the University of New Hampshire and the Massachusetts Institute of Technology.

Mr. Arthur S. Westneat, Jr., of Raytheon Company for his part in the original planning at the University of New Hampshire.

Dr. Wilmot N. Hess and Mr. Robert W. Knecht of NOAA's Environmental Research Laboratories (ERL) and Dr. Robert B. Abel of NOAA's Office of Sea Grant, for organizing continued support of the project after the closing of MMTC.

Ms. Lucy Sloan, representing Nautilus Press, whose work helped project management understand the need for input from local citizens.

The Executive Committee members, who provided overall management direction and policy guidance: Dr. Wilmot N. Hess, Director of ERL; Dr. Robert L. Edwards, Director of the NOAA National Marine Fisheries Service Northeast Fisheries Center; and Mr. Arthur W. Brownell, Commissioner of the Commonwealth of Massachusetts Department of Natural Resources.

The Steering Committee members, who worked with the author, Program Director of NOMES, to crystallize issues and decide on courses of action: Mr. George Kelly, representing NOAA's National Marine Fisheries Service; Mr. Robert Blumberg, Mr. Frank Grice, and Mr. Allen Peterson, representing the Commonwealth of Massachusetts; Dr. Robert Correll of the University of New Hampshire and Mr. Dean Horn of the Massachusetts Institute of Technology, representing the principal investigators.

Mr. John Robinson and Mr. Craig Hooper, who created a preliminary draft EIS for the project as well as a project development plan.

Dr. Harris B. Stewart, Director of NOAA-ERL Atlantic Oceanographic and Meteorological Laboratories, for supporting the test particle dispersion experiment.

And, for assistance in a variety of ways, the U.S. Coast Guard, especially the officers and men of the *White Heath* and the *Pendant*; Mr. Leal Kimrey and Mr. Robert H. Wing of ERL; and Mr. W. Richard Boehmer of the Commonwealth of Massachusetts.

6. REFERENCES

Publications and other documents resulting from Project NOMES, including the principal investigators' reports to the project which form the basis for this document, are identified by an asterisk (*).

Bacescu, M. C. (1971): Substratum animals. In: *Marine Ecology* (edited by O. Kinne) Wiley, London, 1:1291-1322.

Battelle Memorial Institute (1971): Environmental disturbances of concern to marine mining research--a selected annotated bibliography, NOAA Tech. Memo. ERL MMTC-3, 72 pp.

Bigelow, H. B. (1913): Oceanographic cruises of the U.S. Fisheries schooner "Grampus" 1912-1913. *Science*, 38:599-601.

*Bumpus, Dean F. (1974): Review of the physical oceanography of Massachusetts Bay. Woods Hole Oceanographic Institution Tech. Rept. WHOI-74-8, 157 pp.

*Christodoulou, G., J. Connor, and B. R. Pearce (1975): Mathematical modeling of dispersion in stratified waters. Mass. Inst. of Tech., R. M. Parsons Lab. for Water Resources and Hydrodynamics Tech. Rept. 219.

*Coastal Research Corp. (1972): Survey report, NOMES Project, dredge site drogue and dye survey. Final report to Project NOMES, 37 pp. (unpublished manuscript).

Cobb, David A. (1972): Effects of suspended solids on larval survival of the eastern lobster *Homarus Americanus*. In: *Proceedings of the Marine Technology Society 8th Annual Conference*, 395-402.

Commonwealth of Massachusetts (1968): *Massachusetts Landings*, CFS 5141.

Commonwealth of Massachusetts (1971): *Massachusetts Landings*, CFS 5799.

*Connor, J., and J. Wang (1973): Mathematical models of the Massachusetts Bay, Part I: Finite element modeling of two-dimensional hydrodynamic circulations. Mass. Inst. of Tech., R. M. Parsons Lab. for Water Resources and Hydrodynamics Tech. Rept. 172.

Cooper, James D. (1970): Sand and gravel. In: *Mineral Facts and Problems*, U.S. Bureau of Mines Bull. 650, 1185-1199.

Costin, J. M. (1970): Visual observations of suspended-particle distributions at three sites in the Caribbean Sea. *J. Geophys. Res.*, 75:4144-4150.

Cressard, A. P. (1975): Development of marine sand and gravels. Centre National pour L'Exploitation des Oceans, Prelim. Rept., 44 pp.

Cronin, L. E., G. Gunter, and S. H. Hopkins (1971): Effects of engineering activities on coastal ecology. Rept. to Office of Chief of Engineers, U.S. Army Corps of Engineers, 48 pp.

Davis, H. C. (1960): Effects of turbidity producing materials in sea-water on eggs and larvae of the clam *Venus mercenaria mercenaria*. *Biol. Bull.*, 118:48-54.

Davis, C. R. and F. A. Nudi, Jr. (1971): A turbidity bioassay method for the development of prediction techniques to assess the possible environmental effects of marine mining. Offshore Technology Conference Paper No. 1414.

Dayton, P. K., G. A. Robilliard, R. T. Paine, and L. B. Dayton (1974): Biological accommodation in the benthic community at McMurdo Sound, Antarctica. *Ecol. Monogr.*, 44:105-128.

El-Sayed, E. S. (1972): Primary production and standing crop of phytoplankton. In: *Chemistry, Primary Productivity, and Benthic Algae of the Gulf of Mexico*. Serial Atlas of the Marine Environment, Folio 22, edited by V. C. Bushnell, Amer. Georg. Soc., New York, 8 pp.

Flemer, D. A. (1970): Primary production in Chesapeake Bay. *Chesapeake Sci.*, 11:117-129.

*Frankel, S. L., and B. R. Pearce (1974): Determination of water quality parameters in the Massachusetts Bay (1970-1973). Massachusetts Institute of Technology Report No. 174, 342 pp.

Grigg, R. W., and R. S. Kiwala (1970): Some ecological effects of discharged wastes on marine life. *Calif. Fish and Game*, 56:145-155.

Golikov, A. N., and O. A. Scarlato (1973): Comparative characteristics of some ecosystems of the upper regions of the shelf in tropical, temperate, and arctic waters. *Helgolander wiss. Meeresunters*, 24:219-234.

Gray, J. S. (1974): Animal-sediment relationships. In: *Oceanography and Marine Biology-An Annual Review*, (edited by H. Barnes) Hafner, N.Y., 12:223-262.

Harrison, W., and M. L. Wass (1965): Frequencies of infaunal invertebrates related to water content of Chesapeake Bay sediments. *Southeastern Geology*, 6:177-187.

Hess, Harold D. (1971): Marine sand and gravel mining industry of the United Kingdom. NOAA Tech. Rept. ERL 213-MMTC 1, 176 pp., Supt. of Documents, U.S. Govt. Printing Office, Washington, D.C. 20402.

*Hess, W. N., and T. A. Nelson (1975): A test particle dispersion study in Massachusetts Bay to simulate a dredge plume. Offshore Technology Conference Paper No. 2160, 7 pp. plus figures.

Holme, N. A., and A. D. McIntyre (1971): Methods for the study of marine benthos. *Internat. Biol. Prog. Handbook 16*, Blackwell Sci. Publ., Oxford, 334 pp.

Howell, B. R., and R. G. J. Shelton (1970): The effect of china clay on the bottom fauna of St. Austell and Megivissey Bays. *J. Mar. Biol. Ass.*, 50:593:607.

International Council for the Exploration of the Sea (1975): Report of the Working Group on Effects on Fisheries of Marine Sand and Gravel Extraction. Cooperative Research Rept. No. 46, 57 pp.

JBF Scientific Corp. (1973): Interaction of heavy metals with sulfur compounds in aquatic sediments and in dredged material. Rept. for U.S. Army Corps of Engineers.

Jenkins, P. M. (1937): Oxygen production by the diatom *Coscinodicus excentricus* in relation to submarine illumination in the English Channel. *J. Mar. Biol. Ass.*, 22:301-343.

Jerlov, N. G. (1958): Maxima in the vertical distribution of particles in the sea. *Deep-Sea Res.*, 5:173-184.

Krauskopf, K. B. (1956): Factors controlling the concentrations of thirteen rare metals in sea water. *Geochim. et Cosmochim. Acta*, 9:1-32.

Legendre, L. (1971): Production primaire dans la Baie-des-Chaleurs (Golfe Saint-Laurent). *Naturaliste Canadien*, 98:743-773.

*Leimkerhler, W. F., et al. (1974): A two-dimensional finite element dispersion model. ASCE Symposium on Modeling Techniques, *Modeling '75*.

Lie, U., and J. C. Kelley (1970): Benthic infauna communities off the coasts of Washington and in Puget Sound: identification and distribution of the communities. *J. Fish. Res. Bd. Canada*, 27:621-651.

Lloyd, I. J. (1971): Primary production off the coast of northwest Africa. *J. Cons. Perma. Int. Explor. Mer*, 33:312-323.

Loosanoff, V. L. (1961): Effects of turbidity on some larval and adult bivalves. *In: Proc. of Gulf and Carib. Fish. Inst. 14th Ann. Ses.*, 80-94.

Louisiana Wild Life and Fisheries Commission (1971): Cooperative Gulf of Mexico estuarine inventory and study, Louisiana, Phase II: Hydrology, and Phase III: Sedimentology (edited by Barney B. Barrett) 191 pp.

Mandelli, E. F., P. R. Burkholder, T. E. Dohemy, and R. Brody (1970): Studies of primary productivity in coastal waters of southern Long Island, New York. *Mar. Biol.*, 7:153-160.

Marshall, S. M., and A. P. Orr (1928): The photosynthesis of diatom cultures in the sea. *J. Mar. Biol. Ass.*, 15:321-360.

*Mayer, Dennis A. (1975): Examination of water movement in Massachusetts Bay. NOAA Tech. Rept. ERL 328-AOML 17, Supt. of Documents, U.S. Govt. Printing Office, Washington, D.C. 20402.

Meadows, P. S. and J. I. Campbell (1972): Habitat selection by aquatic invertebrates. In: *Advances in Marine Biology*, Academic, N.Y., 10:271-382.

Menzel, D. W., and J. H. Ryther (1960): The annual cycle of primary production in the Sargasso Sea off Bermuda. *Deep-Sea Res.*, 6:351-367.

Mulligan, Hugh F. (1973): Probable causes for the 1972 red tide in the Cape Ann region of the Gulf of Maine. *J. Fish. Res. Bd. Canada*, 30:1363-1366.

Mulligan, Hugh F. (1975): Oceanographic conditions associated with New England red tide blooms. In: *Proceedings of First International Symposium on Toxic Dinoflagellate Blooms*, Mass. Inst. of Tech. Foundation.

National Research Council (1975): *Mining in the Outer Continental Shelf and in the Deep Ocean*, 152 pp.

*Nelson, T. A., P. E. Hatcher, and D. A. Mayer (1977): The character of particle dispersion and water movement in Massachusetts Bay and adjacent waters. *Estuarine and Coastal Marine Science*, in press.

Nichols, F. H. (1970): Benthic polychaete assemblages and their relationship to the sediment in Port Madison, Washington. *Mar. Biol.*, 6:48-57.

Padan, John W. (1972): Possible effects of marine sand and gravel mining. Presentation at Marine Technology Society Conference on Technology Assessment (unpublished manuscript).

Parker, Jon (1974): Phytoplankton primary productivity in Massachusetts Bay. Ph. D. Dissertation, U. of New Hampshire.

Parsons, T. R., and G. C. Anderson (1970): Large scale primary production in the North Pacific between 40°-50°N. *Deep-Sea Res. Oceanogr. Abs.*, 17:765-776.

*Peddicord, R. K., et al. (1975): Effects of suspended solids on San Francisco Bay organisms (Appendix G in dredge disposal study--San Francisco Bay and Estuary). U.S. Army Corps of Engineers Rept., San Francisco District, 205 pp.

Peet, R. K. (1975): Relative diversity indices. *Ecol.*, 56;496-498.

Platt, T. (1971): The annual production by phytoplankton in St. Margaret's Bay, Nova Scotia. *J. Cons. Perma. Int. Explor. Mer*, 33:324-333.

Reish, D. J. (1957): Effect of pollution on marine life. *Industrial Wastes*, 2:114-118.

Reish, D. J. (1961): A study of benthic fauna in a recently constructed boat harbor in Southern California. *Ecol.*, 42;84-91.

Rhoads, D. C. (1974): Organism-sediment relations on the muddy sea floor. In: *Oceanography and Marine Biology; An Annual Review*, (edited by H. Barnes) Hafner, N.Y., 12: 263-300.

Rhoads, D. C., and D. K. Young (1970): The influence on sediment stability and community trophic structure. *J. Marine Res.*, 28:150-178.

Rhoads, D. C., and D. K. Young (1971): Animal-sediment relations in Cape Cod Bay, Massachusetts. II - Reworking by *Molpadio oolitica* (holothuroidea). *Mar. Biol.*, 11:255-261.

Ryther, J. H., and C. M. Yentsch (1958): Primary production of continental shelf waters off New York. *Limnol. and Oceanogr.*, 3:327-335.

Saila, S. B., T. T. Polgar, and B. A. Rogers (1968): Results of studies related to dredged sediment dumping in Rhode Island Sound. *Proceedings of Northeastern Regional Antipollution Conference*, University of Rhode Island, July 22-24, 71-80.

Saila, S. B., S. D. Pratt, and T. T. Polgar (1972): Dredge spoil disposal in Rhode Island Sound. U. Rhode Island Mar. Tech. Rept. No. 2, 48 pp.

Sanders, H. L. (1958): Benthic studies in Buzzards Bay, I: Animal-sediment relationships. *Limnol. and Oceanogr.*, 111:245-258.

Sanders, H. L. (1960): Benthic studies in Buzzards Bay, III: The structure of the soft bottom community. *Limnol. and Oceanogr.*, 5:138-153.

Sanders, H. L. (1968): Marine benthic diversity: a comparative study. *Amer. Nat.*, 102:243-282.

Scheltema, R. S. (1961): Metamorphis of the veliger larvae of *Nassarius obsoletus* (Gastropoda) in response to bottom sediment. *Biol. Bull.*, 120:92-109.

Shannon, C. E., and W. Weaver (1963): *The Mathematical Theory of Communication*. University of Illinois Press.

Sherk, J. A., Jr., and L. E. Cronin (1970): The effects of suspended and deposited sediments on estuarine organisms. University of Maryland Chesapeake Biological Laboratories Rept. No. 70-19, 62 pp.

Sherk, J. A., J. M. O'Connor, and D. A. Neumann (1972): Effects of suspended and deposited sediments on estuarine organisms - Phase II. University of Maryland Chesapeake Biological Laboratories Rept. No. 72-98. 106 pp.

Steeman-Nielsen, E. (1951): The marine vegetation of the Isefjord - a study of ecology and production. *Medd. Komm. Danmarks Fisk. Havund., Ser., Plankton*, 5:1-114.

Sykes, J. E., and J. R. Hall (1970): Comparative distribution of mollusks in dredged and undredged portions of an estuary, with a systematic list of species. *Fish. Bull.*, 68:299-303.

Taylor, D., W. Roland, and J. E. Hughes (1964): Primary productivity in the Chesapeake Bay during the summer of 1964. Ches. Bay Inst. Rept. 34, 67-100.

Teal, J. M., and J. Kanwisher (1966): The use of pCO_2 for the calculation of biological production with examples from waters off Massachusetts. *J. Marine Res.*, 24:1-15.

Tenore, K. R. (1972): Macrobenthos of the Pamlico River Estuary. *Ecol. Monogr.*, 42:51-69, North Carolina.

Thorson, G. (1946): Reproduction and larval development of Danish marine bottom invertebrates with special reference to the planktonic larvae in the Sound (Oresund). *Meddel. Komm. Danmarks Fisk. Havund., Ser., Plankton*, 4:1-523.

Thorson, G. (1957): Bottom communities (sublittoral or shallow shelf). In: *Treatise on Marine Ecology and Paleoecology*, edited by J. W. Hedgepeth, Geol. Soc. Amer. Memoir, 67:461-534.

Thorson, G. (1966): Some factors influencing the recruitment and establishment of marine benthic communities. *Neth. Jour. of Sea Res.*, 3:267-293.

Wilson, D. P. (1954): The attractive factor in the settlement of *Ophelia bicornis* Savigny. *J. Mar. Biol. Ass.*, 33:361-380.

Yentsch, C. S. (1974): Some aspects of the environmental physiology in marine phytoplankton: a second look. In: *Oceanography and Marine Biology, An Annual Review* (edited by Harold Barnes) Hefner, N.Y., 12:41-75.

Yentsch, C. S., P. Morris, and C. M. Yentsch (1971): The physiological state with respect to nitrogen of phytoplankton from low nutrient sub-tropical water as measured by the effect of ammonium on dark carbon dioxide fixation. *Limnol. and Oceanogr.*, 16:859-868.

Young, D. K., and D. C. Rhoads (1971): Animal-sediment relations in Cape Cod Bay, Massachusetts, I: A transect study. *Mar. Biol.*, 11:242-254.

7. Additional Documentation of Project NOMES

*Commonwealth of Mass. and NOAA (1973): New England offshore mining environmental study. Preliminary draft environmental impact statement. 72 pp.

deLara, F. S., and H. F. Mulligan (1977): Cultural requirements of phytoplankton from Massachusetts Bay. Submitted to *Int. Rev. Ges. Hydrobiol.*

Donovan. J. M. (1974): Spring phytoplankton populations in the Great Bay Estuarine System, N.H. M. S. Thesis, U. of New Hampshire, 90 pp.

* Principal Investigators' Reports.

*Grant, C. L., et al. (1974): A study to understand the environmental and ecological impact of marine sand and gravel mining in order to prepare guidelines for mining operations in the sea--chemical characterization of core samples from the dredge site. Final rept. to Project NOMES, University of New Hampshire, 83 pp. (unpublished manuscript).

*Harris, Larry G. (1976): Field studies on benthic communities in the New England Offshore Mining Environmental Study (NOMES). Final rept. to Project NOMES, University of New Hampshire, 130 pp.

Mulligan, H. F. (1973): Probable causes for the 1972 Red Tide in the Cape Ann Region of the Gulf of Maine. 30:1363-1366. *J. Fisheries Research Board, Canada.*

Mulligan, H. F. (1975: Oceanographic conditions associated with New England Red Tide Blooms. *In*: Proceedings of the First International Symposium on Toxic Dinoflagellate Blooms, ed. V. R. LoCicero, Massachusetts Science and Technology Foundation, Wakefield, Mass. 23-40.

*Mulligan, Hugh F. (1976): Phytoplankton and hydrographic studies in the Gulf of Maine: Massachusetts Bay and Bigelow Bight. Final rept. to NOAA/ ERL, Boulder, Colo., 200 pp.

Mulligan, H. F. and R. Beauregard. Hydrographic conditions from Rye, New Hampshire to Boston, Massachusetts, August 1971-August 1972 (unpublished manuscript).

Mulligan, H. F. and F. S. deLara (1974): Phytoplankton. Chapter X - A Socioeconomic and Environmental Inventory of the North Atlantic Region. Sandy Hook to Bay of Fundy. The Research Institute of the Gulf of Maine (TRIGOM), Portland, Maine 1(3): 1-180.

*Setlow, Loren W. (1973): Geological investigation of the Project NOMES dredging site. Massachusetts Dept. of Natural Resources Pub. No. 6937 (61-25-8-73-CR), 58 pp.

Shar, A. and H. F. Mulligan (1977): Phytoplankton: Simulated seasonal mining impacts. In press, *Int. Rev. Ges. Hydrobiol.*

Wessel, and H. F. Mulligan (1977): A taxonomic key to the phytoplankton of Massachusetts Bay. Publication #2. Shoals Marine Laboratory, Cornell University Press. 155 pp.

* Principal Investigators' Reports.

APPENDIX A

Project NOMES Advisory Committees

Because of the obvious future involvement of several Federal agencies when continental shelf mining begins, they were included in the planning of the project. This helped to insure that future Federal needs were addressed, where practicable, in NOMES. An organization finally emerged which became known as the Interagency Coordination Committee.

Local advice was sought both from New England's experts in certain specialties and from concerned citizens. Two committees resulted, both officially reporting to the Commonwealth of Massachusetts: a Technical Advisory Committee and a Local Advisory Committee.

Committee membership as of July 1973 follows:

INTERAGENCY COORDINATION COMMITTEE

NOAA

Robert J. Gallagher
Staff Assistant
Water Resources Div.
National Marine Fisheries Serv.
2300 Whitehaven Court
Washington, D.C. 20007

Craig H. Hooper
Office of Programs
Environmental Research Laboratories
Boulder, Colo. 80302

Amor L. Lane
Office of Assoc. Admin. for
Marine Resources
NOAA
Rockville, Md. 20852

John W. Padan
Program Director Project NOMES
c/o Commissioner
Dept. of Natural Resources
Leverett Saltonstall Building
100 Cambridge St.
Boston, Mass. 02202

Robert D. Wildman
Office of Sea Grant
NOAA
Rockville, Md. 20852

Robert Hanks
National Marine Fisheries Service
Oxford Laboratory
Oxford, Md. 21654

Dr. Wilmot N. Hess
Director
Environmental Research Laboratories
Boulder, Colo. 80302

Robert W. Knecht
Office of Coastal Zone Management
NOAA
Rockwall Building, Room 429A
11400 Rockville Pike
Rockville, Md. 20852

Richard Morse
Assoc. Director for Marine Science
NOAA
Washington, D.C. 20235

Richard B. Perry
National Ocean Survey
NOAA
Rockville, Md. 20852

Corps of Engineers

Gary N. Bigham
Dredge Disposal Study Group
Waterways Experiment Station
Box 631
Vicksburg, Miss. 39180

Dr. David Duane
Coastal Engineering Research Center
Corps of Engineers
5201 Little Falls Rd. NW
Washington, D.C. 20016

John B. McAleer
Planning Division
Office of Chief of Engineers
Corps of Engineers
Washington, D.C. 20314

Steven Onysko
New England Division
Corps of Engineers
Waltham, Mass. 02154

Leo Tobias
Operations Division
Office of Chief of Engineers
Corps of Engineers
Washington, D.C. 20314

Dept. of Interior

William B. Gazdik
U.S. Geological Survey
Washington, D.C. 20242

Peter A. Rutledge
Office of Asst. Sec. for
Mineral Resources
Dept. of Interior
Washington, D.C. 20240

Richard A. Waller
Bureau of Sports Fisheries & Wildlife
Dept. of Interior
Washington, D.C. 20240

Dwight L. Patton
Office of the Asst. Sec. for
Public Land Management
Dept. of the Interior
Washington, D.C. 20240

Donald Truesdell
Bureau of Land Management
Dept. of Interior
Washington, D.C. 20240

Environmental Protection Agency

Victor T. McCauley
Office of Water Programs
Environmental Protection Agency
Washington, D.C. 20460

John J. Mulhern
Pollution Control Analysis Section
Office of Research & Monitoring
Environmental Protection Agency
Washington, D.C. 20460

U.S. Coast Guard

Lt.(jg.) William P. Holt
U.S. Coast Guard
Washington, D.C. 20590

LOCAL ADVISORY COMMITTEE

Mr. Gale Charles
Provincetown Cooperative Fishing Industries
307 Commonwealth Avenue
Provincetown, Mass. 02657

Mr. James Ackert
577 Washington Street
Gloucester, Mass. 01930

Senator John Aylmer
State House, Room 315
Boston, Mass.

Malcolm Graf
Assoc. Comm. Dept. of Public Works
Div. of Waterways, Room 530
100 Nashua Street
Boston, Mass. 02114

Mrs. Rita Barron
League of Women Voters
120 Boylston Street
Boston, Mass. 02116

Mr. Harold Lyman
Saltwater Sportsman, Inc.
10 High Street
Boston, Mass.

Mr. Robert Barlow
Spring Street
Marshfield Hills, Mass. 02051

Mr. Hugh O'Rourke
N.E. Fisheries & Conservation Committee
Boston Fisheries Association
Administration Bldg. Fish Pier
Boston, Mass. 02210

Representative Steve Chmura
State House, Room 473C
Boston, Mass.

Mrs. Grace Saphir
921 E. Squantum Road
Quincy, Mass. 02169

Mr. Arnold Spofford
41 Main Street
Merrimac, Mass. 01860

Mr. Paul Swatek
Sierra Club
373 Huron Avenue
Cambridge, Mass.

Mr. Joseph R. Perini, Jr.
Perini Corp.
73 Mt. Wayte Avenue
Framingham, Mass. 01701

APPENDIX B

Offshore Mining Cycle

In this appendix is described the probable nature of the industry to be expected wnen continental shelf sand and gravel mining becomes a reality off United States shores. Project NOMES was addressed to that phase of the mining cycle of chief concern relative to the marine environment: the effects of excavation by hydraulic dredge. A perusal of the other phases of mining will help the reader place the excavation problems in perspective.

This description is based primarily upon the author's familiarity with the substantial industries that have developed in Europe and Japan. Hess (1971) and International Council for the Explorations of the Sea (1975) provide details on the former.

The following phases of mining are discussed below:

- Exploration
- Excavation
- Shipboard Treatment
- Transportation to Shore
- Shoreside Processing
- Transportation to Market

Exploration

Offshore deposits of sand and gravel are of two principal types: glacial deposits of Pleistocene age, formed when sea level was lower and now submerged, and deposits derived from rivers draining the adjoining land masses. In addition, submerged ancient beach deposits are known to exist.

The easiest to locate will be discovered by bathymetric methods, because they appear as offshore "banks." As the industry develops, acoustic subbottom profiling will be utilized to detect the more difficult to locate deposits. Although these methods will lead to discovery and delineation of size and shape, actual samples must be taken to establish other characteristics of the deposit. There will be two questions to answer at this stage:
(1) Does the deposit contain marketable amounts of sand and/or gravel?
(2) Can the deposit be mined by state-of-art techniques?

With respect to (1), at issue will be the ratio of sand to gravel, and the amount and kind of impurities. The relative amounts of sand and gravel desired will reflect the market situation in each area. In some cases the demand will be for gravel, because sand may be relatively available onshore. In other cases the demand will be for sand. In the United Kingdom (UK) the ideal dredge material is considered to be 40% sand and 60% gravel. Impurities normally consist of clay, silt, fine sand, and shells. Their significance will be discussed below, but generally 5% impurities is considered a maximum for a deposit to be mineable.

Both question (1) and question (2) are answered by probing the deposit with a large-diameter (about 77 cm.) drill sampling tool. This provides a bulk sample which, although not undisturbed, is adequate for deposit evaluation. Sometimes bulk sampling is done by the actual mining of small quantities of sediment. In either case, the amount of material removed from the deposit is limited to a small amount under terms of the UK prospecting license.

There is no indication of any adverse environmental impact associated with the steps in the exploration phase: bathymetry, acoustic sub-bottom profiling, drill sampling, and bulk sampling by mining vessel. However, the final two steps, because thay are conducted by vessels at anchor, could pose a navigation hazard. In addition, the final step could provide a miniature version of the impact associated with the mining phase.

Excavation

Sand and gravel are economically mined from the seafloor in several ways: clam-shell barge, bucket-ladder dredge, and suction dredge. The clam shell technique is gradually phasing out as uneconomic in Europe, where deposits are mined far from shore by large ocean-going hopper dredges, but it supplies over one-half of Japan's production, where numerous small dredges mine fairly close to shore. The bucket ladder dredge is best suited for digging hard bottom formations. The hardware (not to mention the great capital investment) required is not needed for most sand and gravel deposits. In addition, the dredge is relatively unstable for ocean operations in most parts of the world.

The bulk of the 80-vessel UK marine mining fleet consists of suction hopper dredges. Cargo capacities range from about 500 to about 10,000 tons. The trend is toward larger and larger dredges to reduce the cost per unit of material dredged.

Recovery of sand and gravel is done by use of one or more high-head centrifugal pumps dredging a slurry of solids from the seafloor (up to about 30 meters beneath the ocean surface) through a suction pipe. The slurry, about 10% solids, is fed to the hopper(s) where most of the solids remain. The excess water flows overboard, along with fine particles trapped in suspension.

Some dredges recover from a single point while at anchor. This results in the creation of a pit 10 or more feet deep initially, and finally, a pockmarked deposit (fig. 3, p. 7). Some dredges recover while drifting with the changing tidal current, while at anchor. This results in the creation of a crescent-shaped trench about one meter deep. Eventually, the deposit becomes laced with overlapping crescent-shaped trenches. Other dredges recover while drifting unanchored.* This results in numerous shallow trenches, each about 30 cm. in depth (fig. 3).

Most UK mining operations are governed by the tides, operating on a 24-hour cycle whereby the dredges take advantage of high tides for leaving and returning to normally shallow-water cargo discharge points in estuaries or rivers. Generally, a dredge leaves port at the start of ebb tide, steams to its lease area, fills its hopper in a matter of 1 to 3 hours, returns on the flood tide, discharges in 1 to 2 hours, and leaves for sea--all within 24 hours. If the draft of the dredge is not a critical factor, and the lease area is not too far away--130 km. is not uncommon--the cycle may then occupy less than 24 hours.

The majority of deposits worked in the UK are relatively near shore (within 30 km.), comparatively close to market, generally in 20 to 30 meters of water, and from 1 to 10 meters thick.

The mining operation can impact the environment in a variety of ways as described in this report. The main UK fears concern damage to the coastline and to marine life. Interference with navigation and communications is minimized by not permitting mining within 0.8 km. of shipping lanes, submarine cables, pipelines, and marker buoys.

Coastal erosion can be caused in four ways: (1) slumping of the beach profile; (2) changing wave refraction patterns; (3) reduced protection from big waves by the removal of offshore banks; and (4) the removal of material normally part of the onshore-offshore sediment transport budget. The UK has sufficient experience to be able to avoid coastal problems from marine mining.

The main enigma concerns the effect on marine organisms of the turbidity plume and resultant blanket of fines. However, the industry has gone on for so long (since 1926) that there is no way to gain a "before" characterization of marine communities. Therefore, the main focus has been on insuring that mining does not occur on known spawning grounds, such as the clean gravel substrate where herring spawn (International Council for Exploration of the Sea, 1975).

Shipboard Treatment

Most dredges utilize a coarse-grid steel framework across the opening of the suction head. This prevents large rocks from entering the suction pipe. In addition, the coarser sizes are screened off and rejected after passing through the pump. At the other end of the particle size distribution

* It has been predicted that the cutterhead pipeline dredge may find application in the United States, in those cases where mining is done within a few kilometers from shore (National Research Council, 1975). This would in effect transport the discharge plume to shore.

spectrum, fine material is washed overboard, as described in this report. All sizes in-between are retained in the hopper if the market demand coincides with the composition of the deposit. Usually this is not the case and so newer dredges are equipped with vibrating screens whereby all or part of the material--usually the sand fraction--is dumped back into the ocean. On the average, the ratio of sand to gravel mined in the UK is about 70:30. An average market mix requires about 40:60, so gravel dredges frequently dump overboard 2 to 3 tons of sand for every ton of gravel recovered.

Specialized large-capacity dredges of advanced design are being developed in increasing numbers. Such dredges are equipped with highly automated shipboard treatment plants capable of producing a wide range of washed and sized aggregate products at sea and then transporting the cargo to distant ports and unloading a desired sized product or special mix with an automated self-discharging system.

There is no knowledge of the impact of shipboard treatment. But inasmuch as no chemicals are utilized, there are probably but two effects: (1) the dumping of large volumes of sand onto the lease area with a gravel/sand substrate; and, (2) the washing overboard of a greater percentage of fines. The former would alter the bottom habitat but not cause a turbidity plume. The latter would add to the initial turbidity plume problem, but eliminate the washing problem at shoreside.

Transportation to Shore

During transit from dredge site to discharge port, the aggregate settles in the hopper(s) and water is drawn off and pumped overboard. The amount of water lost by this means can be about 10% by weight of the total load. Some very fine particles, in suspension because of the motion of the dredge, are lost overboard in this process.

Shoreside Processing

Shore-based support facilities for the dredges include wharves, stockpiling and processing facilities, and treatment plants. The exact arrangement depends upon the nature of the unloading technique, the processing required to produce marketable aggregate, and the treatment required to clean up waste water.

Some dredges pump ashore with either shore-based pumps or shipboard pumps. In either case the hopper full of sand and gravel is reflooded with river water, and the resultant slurry drawn through a duct in the bottom of the hopper and then into a discharge pipe. From there it is pumped into a large settling tank or pond. The overflow water passes through several stages of settling tanks before it is clean enough to return to the river (or estuary).

Dry discharging is accomplished by clam-shell grabs, elevators and belt conveyors, or scraper-buckets. Self-discharging by scraper buckets, coupled with over-the-side conveyor belts, has been well received in the UK as the most efficient and economical system available. With this system, scraper buckets are rapidly hauled up ramps at the forward part of the hopper and then emptied into an elevated hopper which feeds an over-the-side conveyor belt that carries the material ashore.

Shoreside sand and gravel treatment plants are located near dockside cargo-discharge points, where the material is washed and screened into appropriate sizes which then commonly are blended in specified proportions for local markets.

Excessively large stones are crushed for sale as crushed stone. The remaining sand and gravel is washed (just as it is in inland operations), as it is screened into desired sizes, in order to remove excessive fine material which interferes with the cement-aggregate bond in concrete.

Most UK plants utilize recirculated water for washing, although some use water pumped from a river or estuary. If the water is to be discharged into the environment, and not recycled, large settling tanks are used for cleaning up the water.

Standards have been developed in the UK for salt and shells--two obvious impurities in sea-won aggregate. The sole concern with shell, based on tests by the British Standards Institution, the Greater London Council, and others, involves excessive amounts of hollow shell that reduce concrete strength.

Although salt is thought to accelerate the rate of curing--at the expense of strength--the salt water content of sea-won aggregate is not considered to be a problem. The washing required to remove the fines also removes enough salt that no extra washing is required.

Present UK specifications for sea-dredged aggregates are based largely on standards developed by the Greater London Council, as summarized below:

1) The sodium chloride content of the fine and coarse aggregate must not exceed 0.10% and 0.03%, respectively, by weight of dry aggregate.

2) The total sodium chloride content derived from the aggregates can exceed the above amounts as long as it is not greater than 0.32% by weight of the cement in the mix.

3) Shells that are hollow or of unsuitable shape, in quantities sufficient to adversely affect the permeability or other qualities of the concrete, shall not be permitted.

4) The shell content of the aggregate shall not exceed the following allowable dry-weight percentages of shell: 2% in the $1^1/_2$-inch fraction, 5% in the $^3/_4$-inch fraction, 15% in the $^3/_8$-inch fraction, and 30% in the sand (minus $^3/_{16}$-inch) fraction.

The above specifications, which were said to be subject to amendment at the time of their release (1968), have generally prevailed throughout the industry. However, thay have become somewhat more definitive with respect to shell, and less rigid in the case of sodium chloride content. By late 1970, limits set forth by such bodies as the Greater London Council for the new London Bridge contract have been generally accepted by industry in the London area as well as in most other dredging areas in the UK. These standards are as follows:

Fraction	Maximum % by Weight	
	Shell	Sodium Chloride
$1^1/_2$-inch straight	2	0.1
$^3/_4$-inch straight	5	0.1
$^3/_4$-inch graded	10	0.1
$^3/_8$-inch sand	15	0.1
$^3/_{16}$-inch sand	30	0.2

Transportation to Market

Truck transport has been used in the UK to connect the shoreside processing facilities with urban market outlets. In addition, ready-mixed-concrete plants are now being located alongside sea dredging discharge points.

A recent trend has been the establishment of secondary distribution centers in inland metropolitan areas. These secondary centers are supplied by rail from the primary dredge discharge points, using special rail aggregate-container cars.

APPENDIX C

Benthic Communities Data

Mining impact on the benthos was deemed the most crucial aspect of the project. In the interest of making available a data base for an area that could be mined in the future, if the Commonwealth of Massachusetts so decides, five tables of information are presented. All have been discussed in the text. They are:

- Invertebrate Species

- Algal Species

- Biomass of Algal Species at Hard Substrate Stations

- Densities of Each Motile Species Per Square Meter

- Relative Abundance of Species at Each Station

Table C-1. All Invertebrate Species Identified During the Benthic Communities Study

	Stations													
	H 1	H 8	H 9	H 12	H 14	C 6	D 2	D 3	C 11	M 6	M 7	M 8	M 9	S 10
PORIFERA														
Calcarea														
Clathrina Coriacea		x	x		x									
Leucosolenia botryoides	x	x	x		x									
Scypha ciliata		x	x		x									
Leucosolenia sp.														
Demospongia														
Isodictya deichmannae	x	x	x		x									
Haliclona oculata					x									
Myxilla incrustans		x	x		x									
Myxilla fimbriata			x		x									
Iophon nigricans					x									
Mycalecarmia ovulum	x		x		x	x						x		
Halichondria panicea	x	x	x		x	x								
Cliona truitti														
Cliona vastifica														
Subertechinus hispidus														
Polymastia robusta					x									
Suberites ficus					x									
Halisarca sp.														
CNIDARIA														
Hydrozoa														
Eudendrium carneum														
Eudendrium dispar			x	x	x	x		x	x	x	x	x	x	x
Eudendrium rameum										x	x	x	x	
Eudendrium sp.	x	x	x	x	x	x			x	x	x	x	x	x
Tubularia sp.														
Bougainvillaea carolinensis														
Campanularia verticellata		x	x	x				x						
Campanularia flexuosa														
Campanularia integra	x	x	x	x	x								x	
Campanularia sp.		x	x											
Campanularia volubilis														
Campanularia neglecta														
Obelia articulata	x	x	x	x	x						x		x	
Obelia commissuralis														
Obelia geniculata	x	x	x	x	x	x				x			x	
Obelia sp.									x					
Clytia coronata			x											
Clytia inconspicua														
Clytia johnstoni		x	x	x	x								x	
Clytia raridentata														
Clytia cylindrica														
Gonothyraea loveni			x											
Calycella syringa	x	x			x				x				x	
Opercularella pumila														
Filellum serpens		x	x											
Lafoea sp.			x			x								
Lafoea gracillima		x	x										x	
Halecium articulosum			x											
Halecium sp.	x				x							x	x	
Halecium beani		x				x		x						
Halecium minutum														
Sertularella rugosa	x	x	x											
Sertularella tricuspidata		x	x	x	x	x		x	x	x	x	x	x	x
Sertularella sp.		x							x	x	x			
Sertularella polyzonias		x	x	x	x	x		x				x		x
Thuiaria argentea														
Thuiaria fabricii														
Thuiaria similis														
Thuiaria sp.	x	x	x		x					x				
Hydrallmania falcata		x	x											
Diphasia rosacea														
Diphasia sp.														
Diphasia tamarisca					x									
Sertularia cupressina		x	x	x	x	x		x	x	x	x	x	x	x
Sertularia latiuscula		x			x	x			x	x	x	x	x	
Sertularia argentea						x								
Sertularia similis		x							x					
Dynamena pumila		x								x	x	x	x	
Schizotricha tenella														
Bonneviella sp.		x												
Sertularia sp.		x	x	x	x	x				x	x	x	x	x
Sertularia schmidti			x											
Lafoea pygmaea		x	x											
Sertularella tricus					x	x								
Sertularia tenera						x								
Eudebdrium capillara						x								
Corymorpha pendula														
Obelia articulosum								x						
Sertularia pumila														x

Table C-1. (Continued)

							Stations							
	H	H	H	H	H	C	D	D	C	M	M	M	M	S
	1	8	9	12	14	6	2	3	11	6	7	8	9	10
Anthozoa														
Alcyonium digitatum														
Alcyonium sp.														
Gersemia rubiformis														
Metridium senile		x												
Cerianthus borealis		x				x		x		x				
Alcyonium carneum														
Edwardsia elegans					x	x			x	x	x	x	x	x
Edwardsia sp.														
Halcampa duodecimcirrata									x		x			x
Cerianthus americanus							x	x		x	x	x	x	x
ENTOPROCTA														
Pedicellina cernua														
Barentsia discreta														
ECTOPROCTA														
Crisia eburnea	x	x	x	x	x	x				x				
Crisia denticulata														
Lichenopora hispida	x	x	x	x	x				x	x				
Lichenopora sp.														
Lichenopora verrucaria	x	x	x		x									
Bugula fulva														
Bugula simplex														
Bugula stolonifera														
Bugula turrita		x												
Bugula sp.														
Dendrobeania murrayana	x	x	x		x				x	x				x
Tegella sp.														
Callopora aurita														
Callopora craticula		x												
Tegella armifera														
Turbicellepora canaliculata	x	x	x		x									
Electra pilosa	x	x	x	x	x				x	x	x			x
Hippothoa hyalina	x	x	x	x	x									
Microporella ciliata		x												
Schizomavella auriculata		x	x	x	x					x				
Schizoporella errata		x	x		x					x		x		
Eucratea loricata	x	x	x		x				x	x	x			x
Haplota clavata	x	x	x	x	x					x				
Tricellaria gracilis		x												
Caberea ellisii		x	x		x					x	x	x		x
Tricellaria peachii			x		x					x				
Tubulipora sp.		x	x		x									
Idmonea atlantica			x		x									
Bicellariella ciliata			x		x									
Alcyonidium polyoum														
Bowerbankia gracilis		x												
Bowerbankia sp.														
Porella propingua														
Porella proboscidea														
Porella acutirostris														
Rhamphostomella ovata														
Cribrilina punctata		x		x	x									
Cribrilina annulata		x	x	x										
Hippoporina reticulatopunctata														
Hippoporina sp.														
Hippoporella hippopus														
Flustrellidra hispida														
Porella sp.		x	x	x								x		
Bugula harmsworthi		x												
Callopora lineata		x												
Rhynchozoan rostratum		x												
Scrupocellaria scabra				x										
Tricellaria sp. I				x										
Tricellaria sp. II				x										
Hippoporina contracta			x											
Cribilina sp.	x													
MOLLUSCA														
Aplacophora														
Chaetoderma nitidulum				x						x		x		
Polyplacophora														
Ischnochiton alba		x	x	x	x	x		x	x	x				
Tonicella marmorea	x	x	x	x	x									
Tonicella rubra	x	x	x	x	x				x	x				
Amicula vestita		x							x					
Tonicella sp.						x								
Gastropoda														
Puncturella noachina		x	x	x			x					x		
Puncturella urgancus														
Acmaea testudinalis	x	x		x	x					x		x		
Margarites helicina	x	x	x	x	x	x		x	x			x	x	
Margarites costalis		x												
Moelleria costulata	x	x	x	x	x	x		x	x	x		x		

Table C-1. (Continued)

Stations

	H 1	H 8	H 9	H 12	H 14	C 6	D 2	D 3	C 11	M 6	M 7	M 8	M 9	S 10
Gastropoda (Continued)														
Margarites groenlandica		x	x	x	x	x		x	x				x	
Buccinum undatum	x	x	x	x	x	x		x	x				x	
Neptunea decemcostata						x								
Colus stimpsoni					x									
Colus glyptus			x											
Nassarius trivittata					x	x			x	x	x	x	x	x
Lora bicarincola					x									
Lora incisula	x		x	x					x	x	x	x	x	
Lora pluerotumania									x					x
Lora turricula		x							x	x			x	
Anachis haliaecti										x	x			
Anachis translirata														
Mitrella lunata		x										x		
Mitrella pura			x											
Triphora nigrocincta														
Lacuna vincta		x	x	x	x					x		x		
Lacuna pallidula	x	x	x		x									
Lacuna parva	x													
Alvania areolata	x	x	x	x	x	x			x					
Alvania castanea	x	x	x	x	x	x				x				
Alvania arenaria		x	x	x	x	x		x	x	x		x		
Littorina littorea	x													
Littorina saxatilis														
Assiminea modesta														
Skeneopsis planorbis			x	x	x									
Crepidula fornicata														
Crepidula plana														
Velutina laevigata	x	x	x	x	x				x			x		x
Velutina undata				x										x
Cerithiopsis greeni														
Lunatis heros		x		x										x
Polinices sp.									x					
Polinices nana										x				
Bittium alternatum														
Epitonium sp.														
Omalogyra atomus			x		x									
Diaphana minuta		x	x	x	x	x		x		x		x	x	
Retusa canaliculata														
Cadlina laevis														
Onchidoris aspera	x	x	x	x	x	x		x						
Polycera lessonii	x													
Okenia sp.		x												
Ancula gibbosa			x											
Dendronotus frondosus		x	x	x	x	x								
Doto coronata		x	x	x	x				x	x			x	x
Coryphella sp.														
Pleurobranchaea tarda														
Odostomia semiruda														
Odostomia dianthopila														
Odostomia dealbata														
Odostomia eburnea														
Obostomia gibbosa														
Turbonilla areolata														
Turbonilla bushiana		x											x	
Turbonilla nivea														
Lunatia triseriata				x		x		x	x				x	x
Colus sp.			x		x									
Lunatia immaculata						x			x					
Polycera sp.		--												
Buccinum tenue		x	x											
Natica pusilla					x									
Natica clausa								x						
Colus pygmaeus								x						
Trichotropis bicarinata									x					
Ancula cristata		x												
Mitrella rosacea			x		x									
Mitrella dissimilis			x											
Boreotrophon truncata					x									
Echinochila laevis		x												
Onchidoris sp.		x				x								
Coryphella verrucosa						x		x						
Trichotropis borealis									x					
Philine lima														
Coryphella salmonacea				x										
Lora harpularia									x					
Alvania sp.														
Bivalvia														
Nucula delphinodonta			x	x	x					x	x	x	x	x
Mytilus edulis	x									x		x	x	
Musculus niger		x	x	x	x	x		x	x			x	x	x
Modiolus modiolus	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Crenella decussata		x	x	x	x	x		x	x	x	x	x	x	x

Table C-1. (Continued)

							Stations							
	H 1	H 8	H 9	H 12	H 14	C 6	D 2	D 3	C 11	M 6	M 7	M 8	M 9	S 10
Bivalvia (Continued)														
Crenella glandula			x						x	x	x			
Crenella faba		x	x	x	x	x	x	x	x	x		x		x
Chlamys islandica			x	x	x	x		x						
Aequipecten irradians		x			x									
Placopecten magellanicus		x	x		x				x					
Anomia simplex	x	x	x	x	x	x		x				x		
Astarte undata			x		x	x			x	x	x	x		
Astarte borealis			x			x	x	x	x			x		x
Astarte quadrans									x				x	
Cardita borealis		x	x	x	x		x	x		x				
Arctica islandica		x								x	x	x	x	x
Axinopsis orbiculatus					x					x	x	x	x	
Cerastoderma pinnulatum	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Gemma gemma		x							x	x		x		
Tellina agilis											x		x	x
Macoma calcarea		x	x							x	x	x	x	
Tagelus gibbus														x
Ensis directus													x	x
Siligua costata													x	
Mya arenaria	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Hiatella spp.	x	x	x	x	x	x		x		x	x	x	x	x
Lyonsia hyalina									x	x				
Periploma papyratium					x					x	x	x	x	x
Thracia myopsis										x	x	x	x	
Pandora inornata									x					
Spisula solidissima									x				x	
Asthenothaerus sp.					x			x				x	x	x
Thracia septentrionales					x			x						
Yoldia sapotilla										x		x		
Nuculana pernula												x		
Thracia conradi			x									x		
Anomia aculeata	x	x	x	x	x							x		
Astarte sp.					x	x					x			
Nucula sp.											x	x		
Musculus discors		x	x		x	x			x		x	x		
Astarte elliptica					x	x			x	x	x	x		
Astarte portlandica					x				x	x				
Axinopsis sp.										x	x	x	x	
Macoma balthica													x	
Yoldia subangulata										x				
Aequipecten glyptus										x				
Diplodonta sp.										x				
Thyasira insignis										x	x	x		
Thracia sp.										x	x			
Modiolus sp.	x										x			
Astarte striata					x									
Lyonsia arenosa										x				
Thyasira sp.										x		x		
Crenella sp											x			
Yoldia sp.		x								x		x		
Lyonsia sp.										x				
ANNELIDA														
Polychaeta														
Harmothoe extenuata		x	x	x	x	x		x	x	x		x		
Harmothoe imbricata	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Lepidonotus squamatus	x	x	x	x	x	x				x				x
Leanira tetragona													x	x
Pholoe minuta	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Eteone flava		x				x		x	x				x	x
Eteone longa				x	x	x		x	x	x	x		x	x
Eulalia viridis	x	x	x	x	x	x		x		x	x			x
Phyllodoce groenlandica		x			x	x			x	x	x		x	x
Phyllodoce maculata									x	x	x			
Phyllodoce mucosa		x			x	x	x	x	x	x	x	x	x	x
Syllis armillaris	x	x	x	x	x	x	x	x	x			x	x	x
Exogone dispar			x	x	x	x	x	x	x			x	x	x
Autolytus cornutus			x	x	x		x	x	x					
Nereis pelagica	x	x	x	x	x	x			x	x		x	x	x
Nephtys ciliata	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Nephtys picta						x				x			x	x
Sphaerodorum minutum								x		x				
Glycera capitata		x	x	x	x	x	x	x	x	x	x	x	x	x
Goniada maculata					x				x	x	x	x	x	
Lumbrineris fragilis					x	x			x	x	x	x	x	x
Ninoe nigripes				x					x	x	x	x	x	x
Paraonis sp.						x	x							
Aricidea jeffreysii		x		x	x	x	x	x	x	x	x	x	x	x
Orbinia ornata										x				x
Scoloplos fragilis		x	x	x	x	x			x	x	x	x	x	x
Naineris quadricuspida		x	x	x	x	x	x	x		x			x	x
Nerinides agilis														x
Polydora linga		x				x			x	x	x	x	x	x

Table C-1. (Continued)

	Stations													
	H 1	H 8	H 9	H 12	H 14	C 6	D 2	D 3	C 11	M 6	M 7	M 8	M 9	S 10
Polychaeta (Continued)														
Prionospio sp.		x	x	x	x	x		x	x	x	x	x	x	x
Spio filicornis														
Spio setosa		x	x	x	x	x	x	x	x	x	x	x	x	x
Spio bombyx									x				x	x
Chaetozone setosa														
Cirratulus cirratus		x	x	x	x				x	x				
Dodecaceria concharum	x	x	x	x	x				x	x				
Tharyx acutus		x	x	x	x	x	x	x	x	x	x	x	x	x
Brada sp.		x												
Flabelligera affinis		x	x	x	x	x			x				x	
Pherusa plumosa		x		x					x	x	x	x	x	x
Pherusa affinis		x	x						x	x	x			
Scalibregma inflatum					x				x	x				
Travisia carnea		x	x			x			x	x	x	x		
Notomastus luridus		x	x	x	x	x		x	x	x		x	x	x
Euclymene collaris		x			x	x	x	x	x	x			x	x
Maldane sarsi										x	x	x	x	
Maldanopsis elongata		x	x	x	x									
Praxillella gracilis	x					x				x	x	x	x	x
Myriochele heeri		x	x	x	x	x	x	x	x	x	x	x	x	x
Owenia fusiformis						x	x	x	x		x	x	x	x
Pectinaria granulata	x	x	x	x	x	x		x	x	x	x	x	x	x
Ampharete acutifrons		x				x			x	x		x		
Asabellides oculata		x	x	x	x		x	x	x	x		x	x	
Melinna cristata														
Amphitrite johnstoni		x	x											
Amphitrite cirrata		x	x	x	x									
Nicolea venustula				x										
Polycirrus eximius									x					
Thelepus cincinnatus		x	x	x	x		x	x						
Trichobranchus glacialis														
Chone infundibuliformis				x			x	x	x		x	x	x	x
Euchone rubocincta						x	x	x	x			x	x	x
Myxicola infundibulum										x				
Potamilla reniformis		x	x		x									
Spirorbis borealis	x	x	x	x	x	x		x	x	x		x		x
Spirorbis spirillum	x	x	x	x	x	x		x	x	x	x	x	x	x
Spirorbis violaceus		x	x	x	x									
Hydroides sp.		x	x	x	x	x						x		
Sternapsis scutata	x									x	x	x		x
Harmothoe sp.		x	x	x	x	x	x	x	x	x	x	x	x	x
Autolytus sp					x									
Nereis sp.						x								
Nephtys sp.			x		x			x	x	x	x	x	x	x
Ophelia sp.		x								x	x	x	x	x
Spio sp.		x	x				x	x	x					
Polydora sp.			x		x			x	x		x	x	x	x
Tharyx sp. I		x		x		x		x	x				x	x
Tharyx sp. II								x		x			x	x
Enoplobranchus sanguineus				x	x	x		x	x	x			x	x
Eteone sp.		x	x	x					x	x	x	x	x	x
Drilonereis longa								x						
Fabricia sabella		x		x	x									
Capitella capitata					x								x	
Aphrodita hastata														
Nephtys incisa		x	x	x	x	x		x	x	x	x	x	x	x
Paraonis gracilis		x				x				x	x	x	x	
Lumbrineris tenuis				x		x			x					
Odontosyllis fulgurans									x					
Autolytus alexandri									x					
Praxillura ornata									x			x		
Tharyx sp.		x		x	x	x	x		x	x	x	x	x	x
Scolelepides viridis									x	x		x	x	x
Scoloplos sp.						x								
Phyllodoce sp.	x		x			x								
Spirorbis sp.			x											
Spio sp. I			x											
Spio sp. II			x											
Lampros quadriplicata					x									
Amphitrite sp.					x									
Aphrodida aculeata					x									
Apistobranchus tullbergi										x	x	x		
Potamilla neglecta									x		x			
Clymenella torguata		x	x		x									x
Pherusa sp.										x	x			
Lumbrineris sp.									x					
Drilonereis magna		x				x								
Maldane sp.									x					
Platynereis sp.														
Praxilla gracilis													x	

Table C-1. (Continued)

	Stations													
	H 1	H 8	H 9	H 12	H 14	C 6	D 2	D 3	C 11	M 6	M 7	M 8	M 9	S 10
Polychaeta (Continued)														
Nicolea sp.														
Maldane sp.					x									
Cirratulidae sp.		x	x	x	x									x
Syllidae sp.	x													
Spionidae sp.		x				x						x		x
Pista maculata		x		x	x		x		x	x	x		x	x
Polynoidae sp.			x											
Paranaites speciosa					x					x				
Phyllodocidae sp.			x											
Terebellidae sp.	x	x	x			x			x		x	x		
Amphitrite affinis		x	x	x	x	x		x						
Oligochaeta														
Nerilla antennata														
Hirudinea														
Johanssonia sp.														
Oceanobdella sp.														
Pontobdella sp.														
Trachelobdella sp.														
Hirudinea sp.	x	x											x	
SIPUNCULIDA														
Phascolopsis gouldii						x				x			x	
Phascolion sp.										x				
Phascolion strombi								x				x		
ARTHROPODA														
Pantopoda														
Nymphon grossipes	x	x	x	x	x					x				
Nymphon longitarse		x												
Nymphon macrum		x			x									
Nymphon hirtipes		x	x											
Achelia spinosa	x	x	x	x	x	x		x	x		x			x
Phoxichildium femoratum		x				x			x			x		
Nymphon sp.			x	x					x					
Cumacea														
Eudorella emarginata														
Eudorella sp.														
Diastylis pòlita														
Diastylis sculpta				x	x				x	x	x	x	x	x
Campylaspis a										x	x	x		
Diastylis quadrispinosa				x	x	x				x	x	x	x	x
Lampros quadriplicata					x				x		x		x	x
Diastylis abbreviata														
Petalosaria declivis								x		x	x	x		
Eudorella truncatula											x		x	
Cyclaspis varians											x			
Isopoda														
Cyathura polita										x		x		
Ptilanthura tenuis		x								x		x		
Chiridotea tuftsi												x	x	x
Edotea montosa		x	x		x	x		x	x	x	x	x	x	x
Edotea triloba		x			x					x	x		x	
Idotea baltica			x	x										
Idotea phosphorea	x	x												
Munna fabricii		x	x	x	x	x		x	x					
Janira alta			x		x									
Pleurogonium spinosissimum			x	x	x				x		x	x	x	
Munna munna		x												
Cyathura burbancki		x								x		x	x	
Munna sp.					x									
Cirolana polita		x			x									x
Hemiarthrus abdominalis														
Cirolina sp.														x
Jaera marina		x			x									
Leptognatha caeca													x	
Chiridotea montosa														
Ptilanthura tenuis		x												
Amphipoda														
Unciola irrorata				x	x	x		x	x	x	x	x	x	x
Pseudunciola obliqua								x		x	x	x	x	x
Calliopius laeviusculus	x													
Corophium bonelli		x	x		x				x					x
Corophium crassicorne	x					x		x	x				x	x
Erichthonius rubricornis					x	x		x	x					x
Erichthonius brassiliensis								x						
Dexamine thea														
Pseudohaustorius caroliniensis										x				
Pseudohaustorius borealis														x
Ischyrocerus anguipes	x	x	x	x	x	x		x	x					x
Jassa falcata	x	x	x	x	x	x		x	x				x	x
Anonyx sarsi		x				x			x					x
Hippomedon serratus			x		x				x	x	x	x	x	x
Hippomedon propinquus										x	x	x		x
Orchomene serrata														

Table C-1. (Continued)

	Stations													
	H 1	H 8	H 9	H 12	H 14	C 6	D 2	D 3	C 11	M 6	M 7	M 8	M 9	S 10
Amphipoda (Continued)														
Orchomenella pinguis											x		x	
Orchomenella minuta						x			x		x	x	x	
Acanthonotozoma serratum														
Metopa alderi	x	x	x	x										
Ampelisca aboita									x					
Ampelisca vadorum														
Ampelisca macrocephala	x										x	x		
Ampithoe rubricata														
Leptocheirus pinguis								x	x		x	x	x	x
Casco bigelowi										x				
Maera danae		x						x						
Melita dentata		x	x	x	x	x		x	x	x			x	x
Monoculodes novegicus														
Monoculodes packardi								x						
Monoculodes tuberculatus		x				x		x	x					
Microprotopus ranei														
Photis reinhardi					x			x	x	x	x	x	x	x
Harpinia propinqua										x				
Phoxocephalus holbolli	x	x	x	x	x				x	x	x	x	x	x
Sympleustes glaber	x	x	x	x	x				x	x				x
Stenopleustes gracilis													x	
Dulichia porrecta				x	x	x		x	x	x	x	x	x	x
Dulichia spinosissima						x								
Dulichia monocantha								x						
Pontogeneia inermis	x	x	x	x	x	x			x	x	x	x	x	x
Metopella angusta		x	x	x	x	x		x	x	x	x	x	x	x
Metopella carinata		x	x		x				x					x
Proboloides holmesi		x	x											
Syrrhoe crenulata			x			x		x	x					
Tiron spiniferum						x								
Gitanopsis arctica		x	x		x			x						
Caprella linearis		x	x	x	x	x		x	x	x				
Caprella septentrionalis	x	x	x	x	x	x		x	x	x	x	x		x
Aeginina longicornis		x		x	x	x		x	x			x		x
Monoculodes sp.	x	x	x	x	x	x		x	x	x		x	x	x
Corophium sp.	x	x	x	x	x	x		x	x	x	x	x	x	x
Melita nitida														
Erichthonius sp.					x	x								x
Anonyx lilljeborgi		x		x		x			x	x	x	x	x	x
Orchomenella sp.			x	x	x	x			x	x	x	x	x	x
Parahaustorius sp.														x
Ampelisca sp.	x				x				x	x	x	x	x	x
Acanthohaustorius sp.														x
Metopa sp.		x	x											
Harpinia sp.					x									
Rhachotropis aculeata								x						
Parametopella cypris								x						
Anonyx sp.														
Dulichia sp.					x	x			x				x	
Microprotopus sp.						x								
Unciola sp.		x	x			x								x
Phoxocephalidae sp.											x			
Acanthonotozomatid sp.			x		x									
Lysianassidae sp.														
Tiron sp.			x											x
Syrrhoe sp.			x											
Argissa hamatipes											x	x	x	
Ischyrocerus sp.														
Thoracia														
Balanus balanoides	x	x	x	x	x	x		x				x		
Balanus balanus	x	x	x		x									
Balanus crenatus				x										
Balanus sp.			x											
Brachyura														
Cancer borealis					x					x	x		x	x
Cancer irroratus	x				x	x		x	x		x	x	x	x
Hyas coarctatus			x		x									
Pelia mutica					x									
Anomura														
Pagurus pubescens		x							x					
Pagurus acadianus					x				x					
Pagurus arcuatus												x		
Caridea														
Eualus fabricii	x	x	x		x									
Eualus sp.														
Eualus pusiolus	x	x	x	x	x	x		x			x			x
Caridea palaemonidae														
Palaemonetes sp.														
Lebius polaris		x		x										
Spirontocaris phippsii	x		x											
Eualus gaimardii			x	x										
Crangon septemspinosa										x			x	
Lebius sp.	x													

Table C-1. (Continued)

	Stations													
	H 1	H 8	H 9	H 12	H 14	C 6	D 2	D 3	C 11	M 6	M 7	M 8	M 9	S 10
CHORDATA														
Urochordata														
Didemnum albidium	x	x	x	x	x			x	x			x	x	x
Amaroucium constellatum														
Amaroucium sp.	x	x	x	x	x	x		x					x	x
Amaroucium stellatum														
Chelyosoma macleayanum				x	x							x		
Halocynthia pyriformis			x		x									
Molgula manhattensis														
Molgula sp.	x	x	x	x	x								x	
Boltenia echinata	x	x	x	x	x			x					x	
Boltenia ovifera		x	x	x	x								x	
Dendrodoa carnea	x	x	x	x	x			x					x	
Styela sp.		x	x	x	x			x	x					
Cnemidocarpa mollis	x													
Ascidia sp.		x	x		x									
ECHINODERMATA														
Asteroidea														
Henricia sanguinoleuta	x	x	x	x	x			x						x
Crossaster papposus					x	x								
Solaster endeca			x											
Asterias forbesii	x													
Asterias rubens	x	x	x						x					
Asterias sp.	x	x	x	x	x	x		x	x	x	x	x	x	x
Ophiuroidea														
Ophiura robusta		x	x		x	x	x		x					
Ophioderma sp.	x									x				
Ophiopholis aculeata	x	x	x		x	x	x		x	x		x		
Amphiopholis squamata	x	x	x		x				x					
Echinoidea														
Strongylocentrotus droebachiensis	x	x	x	x	x	x		x	x				x	x
Echinarachnius parma			x					x		x			x	x
Holothuroidea														
Cucumaria frondosa	x	x	x	x	x	x		x		x			x	x
Psolus sp.	x	x	x	x					x				x	
Psolus fabricii		x												
Leptosynapta sp.												x	x	x
Leptosynapta inhaerens														x
Cucumaria sp.	x	x												

Table C-2. Algal Species Identified With Depth of Distribution For Each Species

Depth in Feet	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90
BACILLARIOPHYCEAE:																		
Amphipleura rutilans	x	x		x														
CHLOROPHYCEAE:																		
Chaetomorpha aerea	x	x																
Chaetomorpha linum		x	x	x		x												
Chaetomorpha melagonium	x	x	x	x														
Cladophora sericeae		x	x	x														
Enteromorpha linza		x	x	x														
Monostroma fuscum	x	x																
Monostroma grevillei	x	x																
Spongomorpha arcta	x	x		x														
Spongomorpha spinescens	x	x																
Ulva lactuca	x	x	x	x	x													
PHAEOPHYCEAE:																		
Agarum cribrosum			x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Alaria esculenta	x	x	x	x	x	x			x									
Chorda filum			x	x														
Chordaria flagelliformis		x																
Desmarestia aculeata				x		x			x									
Desmarestia viridis		x	x	x	x													
Ectocarpus confervoides		x	x	x														
Fucus sp.	x																	
Giffordia sandriana	x	x																
Laminaria digitata	x	x	x	x	x	x	x	x	x	x	x	x						
Laminaria longicruris	x	x	x	x	x	x	x		x									
Laminaria saccharina	x	x	x	x	x	x	x	x	x	x	x	x	x					
Pseudolithoderma extensum				x														
Ralfsia verrucosa			x	x														
Sphacelaria racemosa var. arctica				x	x	x												
Spongonema tomentosus				x														
RHODOPHYCEAE:																		
Ahnfeltia plicata	x	x	x	x														
Antithamnion cruciatum							x	x	x	x	x	x		x				
Antithamnion floccosum	x	x	x	x		x	x	x	x	x	x	x	x	x	x	x	x	x
Antithamnion plumula						x			x	x	x	x						
Callithamnion corymbosum		x						x										
Callocolax neglectus			x	x			x	x	x	x	x	x	x	x				
Ceramium rubrum	x	x	x	x				x	x									
Ceratocolax hartzii						x		x	x	x				x	x	x	x	
Chondria baileyana			x	x				x										
Chondrus crispus	x	x	x	x	x	x	x	x	x	x	x	x						
Choreocolax polysiphoniae												x						
Clathromorphum circumscriptum		x	x	x	x	x			x	x		x	x	x	x			
Corallina officinalis		x	x	x		x	x	x										
Cruoriella dubyi						x	x											
Cystoclonium purpureum var. cirrhosum	x	x	x	x	x	x	x	x	x	x	x	x						
Dermatolithon pustulatum											x	x	x					
Euthora cristata	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Gigartina stellata	x	x																
Gymnogongrus norvegicus				x	x	x	x	x	x	x	x	x						
Hildenbrandia prototypus				x	x	x			x	x	x	x						
Leptophytum laevae				x		x	x					x		x	x			
Lithothamnion glaciale		x		x	x	x		x	x	x		x	x	x	x		x	
Lomentaria baileyana	x	x																
Lomentaria clavellosa	x	x																
Lomentaria orcandensis	x	x	x	x														
Membranoptera alata			x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Petrocelis middendorfii				x	x													
Peyssonelia rosenvingii			x	x														
Phycodrys rubens	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Phyllophora pseudoceranoides	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Phyllophora truncata	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Phymatolithon laevigatum		x		x	x	x		x	x	x	x	x	x	x	x			
Phymatolithon rugulosum		x		x	x	x		x	x	x					x		x	
Polyides rotundus			x	x	x	x												
Polysiphonia denudata	x	x																
Polysiphonia lanosa			x	x		x												
Polysiphonia nigra	x	x	x	x														
Polysiphonia nigrescens	x	x	x	x														
Polysiphonia novae-angliae	x	x	x	x														
Polysiphonia urceolata	x	x	x	x		x	x	x	x	x	x	x		x	x	x	x	x
Porphyra miniata		x																
Ptilota serrata				x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Rhodomela confervoides	x	x	x	x				x	x	x		x	x					
Rhodophyllis dichotoma								x	x	x	x	x	x	x	x	x	x	x
Rhodophysema georgii				x	x	x		x									x	
Rhodymenia palmata	x	x	x	x	x	x			x									
Spermothamnion repens				x														

Table C-3. Biomass of Algal Species Sampled at Hard Substrate Stations

Station H1	1971 Oct.	Nov.	1972 Jan.	Mar.	Apr.	July	Aug.	Sept.	Oct.	Nov.	1973 Jan.	Feb.	Mar.	Apr.	Avg.
Agarum		26.60	49.52	38.35	225.5	133.7	42.01	2.91	80.02	60.71	64.77	56.66	40.53	43.14	61.74
cribrosum		5.0%	31.1%	27.8%	89.4%	94.7%	59.2%	79.0%	52.3%	49.3%	40.5%	59.9%	43.9%	54.0%	
Alaria	94.87														6.78
esculenta	97.5%														
Chondrus		0.57	1.27	1.74					0.25			0.06			0.28
crispus		0.1%	0.8%	1.3%					0.2%	0.1%					
Euthora	0.09	1.49	3.33	4.40	1.44	0.21	1.92	0.28	1.08	2.69	1.08	1.26	1.85	0.54	1.55
cristata	0.1%	0.3%	2.1%	3.2%	0.5%	0.1%	2.7%	7.6%	0.7%	2.2%	0.7%	1.3%	2.0%	0.7%	
Laminaria			7.26								18.89	5.59		9.30	2.93
digitata			4.6%								11.8%	5.6%		11.6%	
Laminaria		213.9													15.28
longicruris		40.0%													
Laminaria		101.7							31.65	0.09	5.89	0.05	1.30		10.05
saccharina		19.0%							20.7%	0.1%	3.7%	0.1%	1.4%		
Membranoptera				0.49					0.02	0.61	1.08	0.36	0.48	0.22	0.23
alata				0.4%						0.5%	0.7%	0.4%	0.5%	0.3%	
Phycodrys	1.40	34.89	28.11	17.85	12.16	0.82	4.83		26.53	6.17	18.76	9.51	17.49	6.68	13.23
rubens	1.4%	6.5%	17.7%	13.0%	4.8%	0.6%	6.8%		17.3%	5.0%	11.7%	9.9%	18.9%	8.4%	
Phyllophora	0.76	155.3	69.39	75.10	13.08	3.83	21.93	0.43	13.39	47.24	47.31	21.13	30.31	19.62	37.06
spp.	0.8%	29.1%	43.7%	54.5%	5.2%	2.7%	3.1%	11.7%	8.7%	38.4%	29.6%	21.9%	32.8%	24.5%	
Ptilota	0.15					2.59		0.05	0.13	5.63	2.11	0.64	0.34	0.42	0.86
serrata	0.1%					1.8%		1.4%	0.1%	4.6%	1.3%	0.6%	0.4%	0.5%	
Rhodymenia		0.03													0.002
palmata															
TOTALS	97.27	534.5	158.9	137.8	252.2	141.1	70.69	3.67	153.1	123.1	159.9	95.26	92.30	79.92	149.98

Station H8	1972 Nov.	Dec.	1973 Jan.	Feb.	Mar.	Apr.	May	June	July	Avg.
Agarum cribrosum	31.63	15.02	24.94	35.75	52.17	29.86	34.21	51.80	34.87	34.47
	50.1%	41.6%	35.2%	49.9%	66.6%	43.5%	53.5%	69.7%	53.8%	
Euthora cristata	1.10	0.82	1.02	1.73	1.19	1.66	0.72	0.72	1.23	1.13
	1.7%	2.3%	1.4%	2.4%	1.5%	2.4%	1.1%	1.0%	1.9%	
Membranoptera alata	0.35	0.14	0.32	0.34	0.16	0.34	0.28	0.08	0.27	0.25
	0.6%	0.4%	0.5%	0.5%	0.2%	0.5%	0.4%	0.1%	0.4%	
Phycodrys rubens	1.31	0.41	0.42	0.75	0.65	1.19	1.04	0.60	0.64	0.78
	2.1%	1.1%	0.6%	1.0%	0.8%	1.7%	1.6%	0.8%	1.0%	
Phyllophora spp.	7.60	3.60	16.58	8.24	5.35	14.66	7.52	5.76	7.15	8.50
	12%	10%	23.4%	11.5%	6.8%	21.4%	11.8%	7.8%	11%	
Ptilota serrata	21.10	16.08	27.54	24.72	18.82	20.86	20.08	15.08	20.05	20.48
	33.4%	44.6%	38.9%	34.5%	24%	30.4%	31.4%	20.3%	30.9%	
Rhodophyllis dichotoma				0.07		0.08	0.12	0.28	0.59	0.13
				0.1%		0.1%	0.2%	0.4%	0.9%	
TOTAL GRAMS	63.09	36.07	70.82	71.60	78.34	68.65	63.97	74.32	64.80	65.74

Note: Upper numbers denote biomass (blotted wet weight) in grams per meter squared. Lower numbers give the percentage of the total sample represented for each species.

Table C-3. (Continued)

Station H9	1972 Nov.	1973 Feb.	Mar.	May	June	Avg.
Agarum cribrosum	22.57 44.4%	30.75 47.7%	73.52 73.8%	23.33 46.2%	9.46 22.8%	31.93
Euthora cristata	1.59 3.1%	1.06 1.6%	1.79 1.8%	1.56 3.1%	1.72 4.2%	1.54
Membranoptera alata		0.05 0.1%		0.16 0.3%	0.32 0.8%	0.11
Phycodrys rubens		0.14 0.2%	0.05 0.1%	0.2 0.4%	0.16 0.4%	0.11
Phyllophora spp.	3.04 6%	4.05 6.3%	2.29 2.3%	1.6 3.2%	2.44 5.9%	2.68
Ptilota serrata	23.62 46.5%	28.09 43.6%	21.97 22.1%	23.48 46.5%	26.08 62.9%	24.65
Rhodophyllis dichotoma		0.3 0.5%		0.16 0.3%	1.28 3.1%	0.35
TOTAL GRAMS	50.82	64.44	99.62	50.49	41.46	61.37

Station H12	1973 Jan.	May	June	July	Avg.
Agarum cribrosum	34.96 66.1%	48.56 63.3%	39.44 51%	39.45 67.9%	40.60
Euthora cristata	0.72 1.4%	1.16 1.5%	1.44 1.9%	1.23 2.1%	1.14
Membranoptera alata	0.07 0.1%	0.2 0.3%	0.2 0.3%	0.32 0.5%	0.2
Phycodrys rubens	0.33 0.6%	0.52 0.7%	0.84 1.1%	0.37 0.6%	0.52
Phyllophora spp.	8.92 16.9%	10.56 13.8%	9.96 12.9%	3.31 5.7%	8.19
Ptilota serrata	7.86 14.9%	15.52 20.2%	24.32 31.5%	13.01 22.4%	15.18
Rhodophyllis dichotoma		0.2 0.3%	1.12 1.5%	0.37 0.6%	0.42
TOTAL GRAMS	52.86	76.72	77.32	58.06	66.24

Station H14	1973 Mar.	Apr.	May	July	Avg.
Agarum cribrosum	9.66 39.6%	15.16 42%	7.81 32.3%	13.36 36.6%	11.5
Euthora cristata	1.17 4.8%	1.62 4.5%	0.72 3%	1.56 4.3%	1.27
Phycodrys rubens	0.05 0.2%	0.02 0.1%		0.2 0.5%	0.07
Phyllophora spp.	2.29 9.4%	2.02 5.6%	2.08 8.6%	2.68 7.3%	2.27
Ptilota serrata	11.2 46%	17.3 47.9%	13.36 55.3%	18.44 50.5%	15.08
Rhodophyllis dichotoma			0.2 0.8%	0.28 0.8%	0.12
TOTAL GRAMS	24.37	36.12	24.17	36.52	30.3

Table C-4. Total and Mean Numbers of Individuals of Each Motile Species Found in Densities of $10/m^2$ At Least Once At Some Station*

Number of Cruises	3	6	3	4	5	4	1	1	4	6	5	5	5	5
Stations	H1	H8	H9	H12	H14	C6	D2	D3	C11	M6	M7	M8	M9	S10
Harmothoe		237.4	22.4	93.3	78.6	46.7		10.0	33.3	2.9		0.8	4.1	
extenuata		39.6	7.5	23.3	15.7	11.7		10.0	8.3	0.5		0.2	0.8	
Harmothoe	29.7	61.4	20.8	132.8	89.1	33.3	5.0	17.5	93.1	105.2	0.8	42.2	10.0	3.3
imbricata	9.9	10.2	6.9	33.2	17.8	8.3	5.0	17.5	23.3	17.5	0.2	8.4	2.0	0.7
Leptidonotus	54.6	49.3	20.8	26.8	8.8	0.8				1.1				0.2
squamatus	163.8	296.0	62.4	107.2	44.2	3.3				6.4				0.8
Pholoe	23.6	384.0	140.8	306.9	115.7	89.2	30.0	30.0	173.3	355.5	74.2	508.8	786.6	29.2
minuta	7.9	64.0	46.7	76.7	23.1	22.3	30.0	30.0	43.3	59.2	14.8	101.8	157.3	5.8
Eteone		2.7				2.5		10.0	27.5				16.7	1.6
flara		0.4				0.6		10.0	6.9				3.3	0.3
Eulalia	53.3	42.7	33.1	38.1	26.5	8.3		5.0		0.7	1.7			0.8
viridis	17.8	7.1	11.0	9.5	5.3	2.1		5.0		0.1	0.3			0.2
Phyllodoce		5.3			2.7	6.7	205.0		22.5	0.7	5.0		0.8	9.1
groenlandica		0.9			0.5	1.7	205.0		5.6	0.1	1.0		0.2	1.8
Phyllodoce									47.5	13.6	0.8			
maculata									11.9	2.3	0.2			
Phyllodoce		37.3			29.0	212.5		100.0	479.2	14.1	14.5	23.2	486.6	54.1
mucosa		6.2			5.8	53.1		100.0	119.8	2.3	2.9	4.6	97.3	10.8
Syllis	5.3	162.7	46.9	25.6	38.9	107.5	85.0	7.5	92.5			0.8	1.7	3.3
armillaris	1.8	27.1	15.6	6.4	7.8	26.9	85.0	7.5	23.1			0.2	0.3	0.7
Exogone			5.9	19.2	56.0	1228.3	35.0	465.0	1010.8			11.9	1.7	45.9
dispar			2.0	4.8	11.2	307.1	35.0	465.0	252.4			2.4	0.3	9.2
Nereis	404.6	360.0	63.0	100.3	88.7	3.3			3.3	8.8		2.5	0.6	0.8
pelagica	134.9	60.0	21.0	25.1	17.7	0.8			0.8	1.5		0.5	0.1	0.2
Nephtys	4.6	101.4	23.4	95.5	11.1	38.3	20.0	42.5	397.5	28.0	160.6	14.1	226.7	189.2
ciliata	1.5	16.9	7.8	23.4	2.2	9.6	20.0	42.5	9.9	4.7	32.1	2.8	43.3	37.8
Nephtys						5.0				4.2			32.5	54.2
picta						1.2				0.7			6.5	10.8
Glycera		10.7	5.4	3.2	17.6	318.3	65.0	70.0	125.0	0.7	1.6	4.2	5.8	6.7
capitata		1.8	1.8	0.8	3.5	79.6	65.0	70.0	31.2	0.1	0.3	0.8	1.2	1.3
Goniada					5.0				34.2	223.5	7.4	40.3	14.7	
maculata					1.0				8.5	37.2	1.5	8.1	2.9	
Lumbrineris					6.7	2.5			16.7	145.5	19.2	23.4	3.3	1.6
fragilis					1.3	0.6			4.2	24.2	3.8	4.7	0.7	0.3
Ninoe				4.0					13.3	1912.9	1122.7	631.9	109.2	20.8
nigripes				1.0					3.3	318.8	222.5	106.4	21.8	4.2
Aricidea		21.3		89.6	10.7	29.2	20.0	22.5	400.8	8.9	20.8	8.3	615.8	19.2
jeffreysii		3.5		22.4	2.1	7.3	20.0	22.5	100.2	1.5	4.2	1.7	123.2	3.2
Scoloplos		5.4	2.7	3.2	5.4	13.3			65.0	685.9	304.1	383.7	740.8	65.9
fragilis		0.9	0.9	0.8	1.1	3.3			16.2	114.3	60.8	76.7	148.2	13.2
Naineris		10.7	19.7	3.2	16.0	46.7	15.0	35.0		30.3			8.3	3.3
quadricuspida		1.8	6.6	0.8	3.2	11.7	15.0	35.0		5.0			1.7	0.7
Polydora		5.3				12.5			175.0	5.8	3.7	29.1	217.5	58.3
ligna		0.9				3.1			43.7	1.0	0.7	5.8	43.5	11.7
Spio		48.0	11.2	28.8	17.9	198.3	25.0	62.5	258.3	1668.7	9.3	1661.3	228.4	31.7
setosa		8.0	3.7	7.2	3.6	49.6	25.0	62.5	64.6	278.1	1.9	332.3	45.7	6.3
Spiophanes									3.3				116.6	198.3
bombyx									0.8				23.3	39.7
Cirratulus		58.6	10.7	25.2	10.7				3.3	0.7				
cirratus		9.8	3.6	6.3	2.1				0.8	0.1				
Dodecaceria	16.0	42.7	21.3	230.1	45.3				2.5	0.7				
concharum	5.3	7.1	7.1	57.5	9.1				0.6	0.1				

Note: *The total is the sum of values adjusted to densities per meter square so the mean is also in numbers per meter square. The totals are given above the means for each species.

Table C-4. (Continued)

Number of Cruises	3	6	3	4	5	4	1	1	4	6	5	5	5	5
Stations	H1	H8	H9	H12	H14	C6	D2	D3	C11	M6	M7	M8	M9	S10
Tharyx		53.3	13.3	30.9	11.4	100.0	55.0	12.5	605.0	25.8	0.8	5.8	894.9	25.8
acutus		8.8	4.4	7.7	2.3	25.0	55.0	12.5	151.2	4.3	0.2	1.2	179.0	5.2
Flabelligera		16.0	19.7	9.6	20.2	2.5			2.5				0.8	
affinis		2.7	6.6	2.4	4.0	0.6			0.6				0.2	
Pherusa		5.3		3.2					16.7	13.2	14.7	9.4	40.7	7.5
plumosa		0.9		0.8					4.2	2.2	2.9	1.9	8.1	1.5
Travisia		10.6				13.3			350.8	531.8	10.8	52.5		
carnea		1.8				3.3			87.7	88.6	2.2	10.5		
Notomastus		8.1	3.2	19.2	21.3	12.5		27.5	857.5	64.7		0.8	52.5	4.2
luridus		1.3	1.1	4.8	4.3	3.1		27.5	214.4	10.8		0.2	10.5	0.8
Euclymene		64.0	29.8		92.7	5094.2	840.0	947.5	4932.5	31.7			8.4	3113.3
collaris		10.7	9.9		18.5	1273.5	840.0	947.5	1233.1	5.3			1.7	622.3
Maldane										1831.2	1.7	10.8	0.8	
sarsi										305.2	0.3	2.1	0.2	
Maldaropsis		34.7	21.3	22.4	66.4									
elongata		5.8	7.1	5.6	13.3									
Praxillella	4.6					53.3				171.8	0.8	15.4	3.2	0.8
gracilis	1.5					13.3				28.6	0.2	3.1	0.6	0.2
Myriochele		40.0	5.9	26.7	13.7	37.5	20.0	10.0	228.3	3.3	3.3	63.1	97.4	
heeri		6.7	2.0	6.7	2.7	9.4	20.0	10.0	57.1	0.5	0.7	12.2	19.5	
Owenia						32.5	50.0	10.0	595.8		140.4	6.3	6543.3	12.5
fusiformis						8.1	50.0	10.0	148.9		28.1	1.2	1308.7	2.5
Pectinaria	8.6	162.7	126.4	411.2	145.1	8.3		7.5	115.8	12.8	2.7	24.7	35.0	11.6
granulata	2.9	27.1	21.1	102.8	29.0	2.1		7.5	29.4	2.1	0.5	4.9	7.0	2.3
Asabellides		69.3	8.5	39.5	5.3		20.0	7.5	28.3	1.4		0.7	1.6	
oculata		11.5	1.4	9.9	1.1		20.0	7.5	7.1	0.2		0.1	0.3	
Amphitrite		45.4	24.0	9.6	10.7									
cirrata		7.6	8.0	2.4	2.1									
Nicolea				25.6										
venustula				6.4										
Polycirrus									12.5					
eximius									3.1					
Thelepus		117.3	16.0	73.1	55.1		10.0	15.0						
cincinnatus		19.5	5.3	18.3	11.0		10.0	15.0						
Chone				6.4			10.0	7.5	42.5		0.8	3.6	4.9	1.7
infundibuliformis				1.6			10.0	7.5	10.6		0.2	0.7	1.0	0.3
Euchone						137.5	30.0	30.0	585.0			7.8	30.1	9.1
rubrocincta						34.4	30.0	30.0	146.2			1.6	6.0	1.8
Potamilla		2.7	10.7		2.7									
reniformis		0.4	3.6		0.5									
Spirorbis	2.3	6840.0	3518.9	2417.9	1473.4	15.0		112.5	11.7	1.4		1.6		5.8
borealis	0.8	1140.0	1172.9	604.5	294.7	3.7		112.5	2.9	0.2		0.3		1.2
Spirorbis	2420.	19632.0	6734.	17073.3	7071.2	54.2		160.0	25.8	8.3	0.8	2.5	0.7	4.2
spirillum	806.6	3272.0	2244.6	4268.3	1414.2	13.5		160.0	6.4	1.2	0.2	0.5	0.1	0.8
Spirorbis		50.6	321.1	164.3	86.8									
violaceus		8.4	107.0	41.1	17.4									
Sternapsis	2.3									1232.4	1.6	3.3		1.6
scutata	0.8									205.4	0.3	0.7		0.3
Nucula			9.6	3.2	2.7					904.6	53.4	72.0	89.1	2.5
delphinodonta			3.2	0.8	0.5					150.8	10.7	14.4	17.8	0.5
Musculus		349.3	297.6	299.7	235.7	19.2		5.0	18.3			5.9	0.8	0.8
niger		58.2	99.2	74.9	47.1	4.8		5.0	4.6			1.2	0.2	0.2
Modiolus	2431.8	2258.7	185.1	256.3	211.3	30.8	5.0	22.5	146.7	16.3	118.5	61.2	1501.7	383.4
modiolus	810.6	376.3	61.7	64.1	42.3	7.7	5.0	22.5	36.7	2.7	23.7	12.2	300.3	76.7
Crenella		29.3	66.7	61.9	120.9	21.7		17.5	135.8	69.6	28.5	24.1	0.8	1.6
decussata		4.9	22.2	15.5	24.2	5.4		17.5	33.9	11.6	5.7	4.8	0.2	0.3

Table C-4. (Continued)

Number of Cruises	3	6	3	4	5	4	1	1	4	6	5	5	5	5
Stations	H1	H8	H9	H12	H14	C6	D2	D3	C11	M6	M7	M8	M9	S10
Crenella			8.0						62.5	12.9	1.7			
glandula			2.7						15.6	2.1	0.3			
Crenella		10.6	42.7	10.4	31.3	25.0	10.0	45.0	190.0	1.5		7.8		0.8
faba		1.8	14.2	2.6	6.3	6.2	10.0	45.0	47.5	0.2		1.5		0.2
Aequipecten		2.7		10.7										
irradians		0.4		2.1										
Anomia	6.9	90.6	29.9	316.8	511.3	5.0		7.5				2.5		
simplex	2.3	15.1	9.9	79.2	102.3	1.2		7.5				0.4		
Astarte			17.6		15.1	3.3			15.0	22.3	12.0	106.4		
undata			5.9		3.0	0.8			3.7	3.7	2.4	21.3		
Astarte			2.7			24.2	10.0	50.0	20.0			20.0		0.8
borealis			0.9			6.0	10.0	50.0	5.0			4.0		0.2
Cardita		2.7	8.5	3.2	5.0		5.0	45.0		0.8				
borealis		0.4	2.8	0.8	1.0		5.0	45.0		0.1				
Artica		2.7								18.3	11.3	16.5	254.1	9.9
islandica		0.4								3.0	2.3	3.3	50.8	2.0
Axinopsis					5.3					62.8	32.2	30.0	40.8	
orbiculatus					1.1					10.5	6.4	6.0	8.2	
Cerastoderma	42.1	109.3	114.2	52.0	346.7	125.0	10.0	50.0	44.2	69.6	71.5	92.1	125.8	80.9
pinnulatum	14.0	18.2	38.1	13.0	69.3	31.2	10.0	50.0	11.0	11.6	14.3	18.4	25.2	16.2
Tellina											4.7		127.6	15.0
agilis											0.9		25.5	3.0
Mya	5.3	149.4	64.6	63.7	42.0	10.8	10.0	15.0	7.5	37.9	7.6	13.7	10.1	0.8
arenaria	1.8	24.9	21.5	15.9	8.4	2.7	10.0	15.0	1.9	6.3	1.5	2.7	2.0	0.2
Periploma					10.3					280.8	16.4	8.0	20.8	2.5
papyratium					2.1					46.8	3.3	1.6	4.2	0.5
Thracia										77.8	15.0	224.6	9.1	
myopsis										13.0	3.0	44.9	1.8	
Leptocheirus								25.0	315.8		2.8	2.5	5.0	7.5
pinguis								25.0	78.9		0.6	0.5	1.0	1.5
Unciola				85.9	253.3	2343.3		455.	13001.7	12.1	0.8	5.8	16.7	137.6
irrorata				21.5	50.7	585.8		455.	3250.4	2.0	0.2	1.2	3.3	27.5
Pseudunciola								2.5		4.0	5.7	33.9	1382.5	2155.8
obliqua								2.5		0.7	1.1	6.8	276.5	431.2
Corophium		16.0	21.3		2.3				5.0					0.8
bonelli		2.7	7.1		0.5				1.2					0.2
Corophium	25.1					141.7		280.0	180.0				69.2	25.8
crassicorne	8.4					35.4		280.0	45.0				13.8	5.2
Erichthonius					2.7	22.5		12.5	7.5					0.8
rubricornis					0.5	5.6		12.5	1.8					0.2
Ischyrocerus	185.1	1642.6	396.3	448.5	404.2	7.5		10.0	18.3					27.5
anguipes	68.3	273.8	132.1	112.1	80.8	1.9		10.0	4.6					5.5
Jassa	1510.9	64.0	2.7	12.8	5.3	2.5		5.0	107.5				4.2	148.3
falcata	503.6	10.7	0.9	3.2	1.1	0.6		5.0	26.9				0.8	29.7
Anonyx		2.7				5.0			10.0					1.7
sarsi		0.4				1.2			2.5					0.3
Hippomedon			2.7		5.3				2.5	14.0	15.8	21.3	5.8	35.8
serratus			0.9		1.1				0.6	2.3	3.2	4.3	1.2	7.2
Hippomedon										15.0	0.8	0.8		4.2
propinquus										2.5	0.2	0.2		0.8
Orchomenella						2.5			12.5		1.7	1.7	11.7	
minuta						0.6			3.1		0.3	0.3	2.3	
Melita		37.3	8.6	56.5	30.4	13.3		20.0	17.5	2.3			0.8	0.8
dentata		6.2	2.9	14.1	6.1	3.3		20.0	4.4	0.4			0.2	0.2
Monoculodes		5.3				7.5		12.5	20.0					
tuberculatus		0.9				1.6		12.5	5.0					

Table C-4. (Continued)

Number of Cruises	3	6	3	4	5	4	1	1	4	6	5	5	5	5
Stations	H1	H8	H9	H12	H14	C6	D2	D3	C11	M6	M7	M8	M9	S10
Photis					50.7			2.5	2.5	10.0	123.3	50.9	996.6	50.0
reinhardi					10.1			2.5	0.6	1.7	24.7	10.2	199.3	10.0
Phoxocephalus	9.1	37.4	22.4	6.4	7.7				2.5	11.3	1.6	5.7	24.1	4.2
holbolli	3.0	6.2	7.5	1.6	1.5				0.6	1.9	0.3	1.1	4.8	0.8
Sympleustes	18.3	813.3	468.2	261.3	460.2				2.5	5.0				7.5
glaber	6.1	102.2	156.1	65.3	92.0				0.6	0.8				1.5
Dulichia				3.2	5.0	6.7		5.0	2.5	0.8	4.4	0.7	17.5	7.4
porrecta				0.8	1.0	1.7		5.0	0.6	0.1	0.9	0.1	3.5	1.5
Pontogeneia	320.0	1501.3	252.8	1497.3	319.6	14.2			17.5	0.8	1.7	3.8	2.5	55.0
inermis	106.6	250.2	84.3	374.3	63.9	3.5			4.4	0.1	0.3	0.8	0.5	11.0
Metopella		714.6	428.8	300.5	199.3	3.3		2.5	15.0	1.5	6.0	3.2	9.2	6.7
angusta		102.3	142.9	75.1	39.9	0.8		2.5	3.7	0.2	1.2	0.6	1.8	1.3
Metopella		32.0	10.7		2.3				7.5					8.3
carinata		5.6	3.6		0.5				1.9					1.7
Proboloides		37.3	5.3											
holmesi		6.2	1.8											
Syrrhoe			2.7			35.0		12.5	7.5					
crenulata			0.9			8.7		12.5	1.9					
Caprella	268.2	738.5	50.7	124.0	232.3	2.5		10.0	20.0	0.7				
linearis	89.4	106.4	16.9	31.0	46.5	0.6		10.0	5.0	0.1				
Caprella	2501.4	2591.9	126.4	1003.7	659.4	24.2		65.0	40.0	1.4	0.8	1.5		4.2
septentrionalis	833.8	431.9	42.1	250.9	131.9	6.0		65.0	10.0	0.2	0.2	0.3		0.8
Aeginina		40.0		5.3	21.9	8.3		20.0	9.2			1.7		2.5
longicornis		6.7		1.3	4.4	2.1		20.0	2.3			0.3		0.5
Chaetoderma				4.0						5.6		21.9		
nitidulum				1.0						0.9		4.4		
Ischnochiton		245.4	98.7	253.3	178.7	203.3		70.0	216.7	0.8				5.8
alba		40.9	32.9	63.3	35.7	50.8		70.0	54.2	0.1				1.2
Tonicella	4.6	48.0	23.0	75.7	23.6									
marmorea	1.5	8.0	7.6	18.9	4.7									
Tonicella	41.9	834.8	314.7	532.3	357.6				3.3	2.5				
rubra	14.0	139.1	104.9	133.1	71.5				0.8	0.4				
Nymphon	4.6	74.7	2.7	9.6	9.4					0.7				
grossipes	1.5	12.4	0.9	2.4	1.9					0.1				
Achelia	114.3	784.0	262.4	108.3	141.0	2.5		2.5	5.0		3.3			1.7
spinosa	38.1	130.7	87.3	27.1	28.2	0.6		2.5	1.2		0.7			0.3
Phoxichilidium		2.7				17.5			15.8			1.4		
femoratum		0.4				4.4			3.9			0.3		
Eudorella					13.3				14.2	20.3	51.0	58.7	37.4	14.9
emarginata					2.5				3.5	3.4	10.2	11.7	7.5	3.0
Diastylis	2.3	2.7							47.5	5.1	7.5	0.8	81.7	15.8
polita	0.8	0.4							11.9	0.8	1.5	0.2	16.3	3.2
Cyathura										44.9		4.2		
polita										7.5		0.8		
Ptilanthura		5.3								29.6		1.6		
tenuis		0.9								4.9		0.3		
Chirodotea												2.2	181.8	10.1
tuftsi												0.4	36.4	2.4
Edotea		40.0	5.3		98.7	15.0		2.5	31.7	360.6	460.3	388.2	420.0	87.4
montosa		6.7	1.8		19.7	3.7		2.5	7.9	60.1	92.1	77.6	84.0	17.5
Edotea		2.7			2.7					19.0	15.0		1.7	
triloba		0.4			0.5					3.2	3.0		0.3	
Idotea	93.7	2.7												
phosphorea	31.2	0.4												
Balanus	22.9	104.0	99.8	255.2	1034.9	13.3		5.0				1.4		
balanoides	7.6	17.3	33.3	63.8	207.0	3.3		5.0				0.3		

Table C-4. (Continued)

Number of Cruises	3	6	3	4	5	4	1	1	4	6	5	5	5	5
Stations	H1	H8	H9	H12	H14	C6	D2	D3	C11	M6	M7	M8	M9	S10
Eualus	29.7	72.1	32.0		74.7									
fabricii	9.9	12.0	14.0		14.9									
Eualus	9.1	314.8	239.5	95.7	228.2	10.8		10.0			0.8			1.6
pusiolus	3.0	52.5	79.8	23.9	45.6	2.7		10.0			0.2			0.3
Henricia	22.9	215.9	46.9	64.0	19.7			5.0						0.8
sanguinoleuta	7.6	36.0	15.6	16.0	3.9			5.0						0.2
Asterias	74.7	200.0	64.0						2.5					
rubens	24.9	33.3	21.3						0.6					
Ophiura		338.7	149.3		297.4	3.3	5.0		5.8					
robusta		56.4	49.8		59.5	0.8	5.0		1.4					
Ophiopholis	156.3	893.3	386.6		567.4	23.3	15.0		3.3	1.4		0.7		
aculeata	52.1	148.9	128.9		113.5	5.8	15.0		0.8	0.2		0.1		
Amphipholis	67.0	85.4	32.0		56.8				10.0					
squamata	22.3	14.2	10.7		11.4				2.5					
Strongylocentrotus	67.8	526.3	297.6	564.0	619.3	277.5		82.5	79.2				7.5	5.8
droebachiensis	22.6	87.7	99.2	141.0	123.9	69.4		82.5	19.8				1.5	1.2
Echinarachnius			2.7					2.5		0.8			58.2	34.3
parma			0.9					2.5		0.1			17.6	6.9
Cucumaria	13.1	645.4	61.9	49.1	47.2	5.0		2.5		0.7			0.8	0.8
frondosa	4.4	107.6	20.6	12.3	9.4	1.2		2.5		0.1			0.2	0.2
Puncturella		50.7	30.4	3.2	20.0			5.0						0.8
noachina		8.4	10.1	0.8	4.0			5.0						0.2
Acmaea	16.7	34.7	3.2	18.1	10.7					0.8		4.2		
testudinalis	5.6	5.8	1.1	4.5	2.1					0.1		0.8		
Margarites	92.2	199.9		10.4	20.6	27.5		12.5	28.3			0.8		1.7
helicina	30.7	33.3		2.6	4.1	6.9		12.5	7.1			0.2		0.3
Moelleria	2.3	376.0	91.2	247.7	224.4	41.6		72.5	27.5	0.8		1.6		0.8
costulata	0.8	62.7	30.4	61.9	44.9	10.4		72.5	6.9	0.1		0.3		0.2
Margarites		74.7	50.7	44.0	169.1	19.1		25.0	15.0					0.8
groenlandica		12.4	16.9	11.0	33.8	4.8		25.0	3.7					0.2
Buccinum	2.3	61.3	11.2	45.9	22.9	22.5		20.0	9.2					2.5
undatum	0.8	10.2	3.7	11.5	4.6	5.6		20.0	2.3					0.5
Colus					14.7									
stimpsoni					2.9									
Nassarius					10.7	5.0			157.5	78.2	90.0	34.8	42.5	69.9
trivittata					2.1	1.2			39.4	13.2	18.0	7.0	8.5	14.0
Lora									20.0					0.8
pleurotumania									5.0					0.2
Lora		2.7							10.0	2.1			0.8	
turricula		0.4							2.5	0.3			0.2	
Anachis										21.7	4.2			
haliaecti										3.6	0.8			
Lacuna		223.9	115.2	707.7	190.6					0.7		0.8		
vincta		37.3	38.4	178.9	38.1					0.1		0.2		
Lacuna	369.6	72.0	8.0		5.3									
pallidula	123.2	12.0	2.7		1.1									
Alvania	25.9	53.4	114.7	3.2	133.6	3.3			3.3					
areolata	8.6	8.9	38.2	0.8	26.7	0.8			0.8					
Alvania	2.3	280.0	83.2	97.6	194.3	2.5			2.5	0.7				
castanea	0.8	46.7	27.7	24.4	38.9	0.6			0.6	0.1				
Alvania	160.1	74.2	116.5	53.6	11.7		2.5	7.5	0.7			4.1		
arenaria	26.7	24.7	29.1	10.7	2.9		2.5	1.9	0.1			0.8		
Velutina	16.7	16.0	14.4	10.4	45.6							0.8		0.8
laevigata	5.6	2.7	4.8	2.6	9.1							0.2		0.2
Diaphana		29.3	20.8	14.9	27.8	2.5		22.5		0.8		0.8	2.5	
minuta		4.9	6.9	3.7	5.6	0.6		22.5		0.1		0.2	0.5	

Table C-4. (Continued)

Number of Cruises Stations	3 H1	6 H8	3 H9	4 H12	5 H14	4 C6	1 D2	1 D3	4 C11	6 M6	5 M7	5 M8	5 M9	5 S10
Onchidoris	82.3	18.6	5.4	10.7	16.0	3.3		2.5						
aspera	27.4	3.1	1.8	2.7	3.2	0.8		2.5						
Polycera	56.4													
lessonii	18.8													
Anomia	9.1	40.0	16.0	41.6	287.6							2.5		
aculeata	3.0	6.6	5.3	10.4	57.5							0.5		
Enoplobranchus				11.7	29.3	29.2		17.5	79.2	2.5			9.1	0.8
sanguineus				2.9	5.9	7.3		17.5	19.8	0.4			1.8	0.2
Nephtys		13.4	2.7	22.4	21.4	10.0		2.5	79.2	15.8	49.3	26.7	155.0	220.8
incisa		2.2	0.9	5.6	4.3	2.5		2.5	19.8	2.6	9.9	5.3	31.0	44.2
Paraonis		2.7				23.3				240.0	4.7	76.6	0.8	
gracilis		0.4				5.8				40.0	0.9	13.3	0.2	
Lumbrineris				3.2		2.5			35.0					
tenuis				0.8		0.6			8.7					
Odontosyllis									10.0					
fulgurans									2.5					
Praxillura									3.3			11.7		
ornata									0.8			2.3		
Scolelepides									27.5	2.5		1.4	0.8	0.8
viridis									6.9	0.4		0.3	0.2	0.2
Diastylis				3.2	5.3				65.8	9.9	260.7	8.8	682.5	135.9
sculpta				0.8	1.1				16.4	1.6	52.1	1.8	136.5	27.2
Anonyx		5.3		9.6		15.8			40.0	46.3	10.3	32.4	4.1	1.7
lilljeborgi		0.9		2.4		3.9			10.0	7.7	2.1	6.5	0.8	0.3
Munna		21.4	21.3	62.9	33.1	5.0		2.5	7.5					
fabricii		3.6	7.1	13.2	6.6	1.2		2.5	1.9					
Janira			51.7		2.3									
alta			17.2		0.5									
Lunatia				5.3		12.5		5.0	2.5				35.1	30.0
triseriata				1.3		3.1		5.0	0.6				7.0	6.0
Musculus		8.1	112.0		88.0	3.3			2.5		1.7	0.8		
discors		1.3	37.3		17.6	0.8			0.6		0.3	0.2		
Astarte					7.7	3.3			10.0	2.4	2.5	15.8		
elliptica					1.5	0.8			2.5	0.4	0.5	3.2		
Lampros					2.3				2.5		3.5		83.4	13.3
quadriplica					0.5				0.6		0.7		16.7	2.7
Diastylis				6.4	14.9	29.2			5.0	2.5	21.1	16.4	8.3	5.8
quadrispinosa				1.6	3.0	7.3			1.2	0.4	4.2	3.3	1.7	1.2
Lunatia						25.8			20.6					
immaculata						6.4			5.1					
Cyathura		32.0								51.7		11.5	2.5	
burbancki		5.3								8.6		2.3	0.5	
Edwardsia		2.7	6.4	3.2	5.3				29.2	1.6	16.0	16.2	52.4	140.1
elegans		0.4	2.1	0.8	1.1				7.3	0.3	3.2	3.2	10.5	28.0
Apistobranchus										10.8	8.0	0.7		
tullbergi										1.8	1.6	0.1		
Clymenella		8.0	21.3		5.3									2.5
torquata		1.3	7.1		1.1									0.5
Mitrella			12.8		24.0									
rosacea			4.2		4.8									
Mitrella			13.3											
dissimilis			4.4											
Halcampa									2.5				40.8	
duodecimcirrata									0.6				8.2	
Eudorella											15.0		1.7	
truncatula											3.0		0.3	

Table C-5. A Comparison of the Relative Abundance of Species At Each Station*

STATION H1	CRUISE						
SPECIES	14	15	16	17	18	19	20
Caprella septentrionalis	1	3	1	2			
Modiolus modiolus	2	5		1			
Spirorbis spirillum	3	1					
Nereis pelagica	4	9					
Lacuna pallidula	5	11					
Hiatella sp.	6	15		3			
Lepidonotus squamatus	7	12					
Asterias rubens	8						
Ophiopholis acculeata	9	13					
Eulatia viridis	10						
Achielia spinosa	11	16					
Caprella linearis	12	7	2	4			
Idotea phosphorea	13	18					
Cerastoderma pinnulatum	14	32					
Strongylocentrotus droebachiensis	15	20					
Polycera lessonii	16	25					
Amphiopholis squamata	17	19					
Margarites helicina	18	14					
Alvania areolata	19						
Dodecaceria concharum	20						
Onchidoris aspera	21	17					
Jassa falcata		2					
Modiolus sp.		4					
Pontogeneia inermis		6					
Ischyrocerus anguipes		8					
Asterias sp.		10					
Corophium sp.		21					
Tonicella rubra		22					
Harmothoe imbricata		23					
Eualus fabricii		24					
Corophium crassicorne		26					
Balanus balanoides		27					
Henricia sanguinoleuta		28					
Phloe minuta		29					
Sympleustes glaber		30					
Phyllodoce sp.		31					
Ophioderma sp.		33					
Acmaea testudinalis		34					
Velutina laevigata		35					
Phyllodocida sp.		36					
Hirudinea sp.		37					
Spirorbis borealis		38					

STATION H8	CRUISE						
SPECIES	14	15	16	17	18	19	20
Spirorbis borealis		1	2	2	3	3	2
Spirorbis spirillum		2	1	1	1	1	1
Ophiopholis aculeata		3	27	18	10	14	21
Caprella septentrionalis		4	4	8	7	2	3
Asterias sp.		5	7	5	6	8	6
Achelia spinosa		6	19	12	12	7	7
Hiatella spp.		7	17	11	33	31	5
Tonicella rubra		8	12	7	11	12	4
Margarites helicina		9	13	15			
Lacuna pallidula		10					
Cucumaria sp.		11					
Lepidonotus squamatus		12	30	27	30	20	37
Eualus fabricii		13					
Strongylocentrotus droebachiensis		14	10	13	13	18	17
Pholoe minuta		15	31	19	20	19	13
Ophiura robusta		16			17	17	19
Caprella linearis		17	14	10	16	6	11
Alvania castanea		18	33	26	18	24	30
Molleria costulata		19	20	25	24	21	12
Nereis pelagica		20	15	14	15	23	26
Modiolus modiolus		21	24	9	2	11	10
Anomia simplex		22		30			54
Henricia sanguinoleuta		23	23	36	25	25	35
Ischnochiton alba		24	26	23	34	36	15
Musculus niger		25	22	16	19	22	14
Amphiopholis squamata		26				32	44
Cerastoderma pinnulatum		27	28		45	43	49
Puncturella noachina		28					45

STATION H8 (Continued)	CRUISE						
SPECIES	14	15	16	17	18	19	20
Hydroides sp.		29			57		
Mya arenaria		30	29		32	34	28
Ischyrocerus anguipes			3	3	5	5	25
Sympleustes glaber			5	17	9	10	16
Metopella angusta			6	6	8	13	50
Eualus pusiolus			8	28	21	39	53
Pontogeneia inermis			9		4	4	9
Lacuna vincta			11	29	26	27	51
Maldanidae sp.			16	20	61		36
Jassa falcata			18		46		
Alvania arenaria			21	34	35		22
Pectinaria granulata			25	39	38	42	20
Thelepus cincinnatus			32	21	31		48
Corophium sp.			34		14	29	58
Buccinum undatum			35		50		40
Cucumaria frondosa			36	4	29	9	18
Diaphana minuta			37				
Anomia aculeata			38				56
Harmothoe imbricata			39	32		50	41
Eulalia viridis			40			45	
Dodocaceria concharum			41				38
Spirorbis violaceus			42		44		
Phoxocephalus holbolli			43		58	53	
Balanus balanoides			44	31	41		31
Margarites groenlandica			45	37	52	55	46
Alvania areolata			46	38	60	56	
Harmothoe sp.			47		22	37	8
Nephtys incisa			48				
Munna fabricii			49				
Edotea montosa				22			
Cyathura burbancki				24			
Harmothoe extenuata				35	27	16	34
Metopella carinata				33	54		
Metopa sp.					23		
Syllis armillaris					28	28	23
Nephtys ciliata					36	46	27
Proboloides holmesi					37		
Cirratulus cirratus					39	51	52
Asabellides oculata					40		39
Tharyx acutus					42	33	
Maldanopsis elongata					43		
Euclymene collaris					47	30	
Myriochele heeri					48	41	
Amphitrite cirrata					49		43
Crenella decussata					50		
Corophium bonelli					51		
Spio setosa					53	47	42
Tonicella marmorea					55	48	55
Glycera capitata					56		
Psolus sp.						26	
Aeginina longicornis						35	
Nymphon grossipes						38	29
Phyllodoce mucosa						40	
Spionidae sp.						44	
Spio sp.						49	
Maldanopsis elongata						52	
Acmaea testudinalis						54	
Asterias rubens							24

STATION H9	CRUISE						
SPECIES	14	15	16	17	18	19	20
Spirorbis spirillum		1		1	1		
Spirorbis borealis		2		2	2		
Ophiopholis aculeata		3			9		
Metopella angusta		4		19	5		
Musculus discors		5					
Ischyrocerus anguipes		6		6	13		
Sympleustes glaber		7		7	3		
Tonicella rubra		8		14	6		
Ophiura robusta		9			19		
Achelia spinosa		10		12	15		
Hiatella sp.		11		4	20		
Lepidonotus squamatus		12			54		
Strongylocentrotus droebachiensis		13		9	16		
Eualus pusiolus		14		17	12		

*All species with densities of 10 per meter square or greater are ranked in order of abundance. Data are from monthly cruises, February through August 1973.

Table C-5. *(Continued)*

STATION H9 SPECIES	CRUISE 14	15	16	17	18	19	20
Spirorbis violaceus		15		3	21		
Asterias sp.		16		8	8		
Asterias rubens		17			34		
Alvania arenaria		18		28	61		
Alvania castanea		19		32	30		
Lacuna vincta		20		23	26		
Anomia simplex		21					
Caprella septentrionalis		22			17		
Cucumaria frondosa		23			29		
Alvania areolata		24		18	37		
Eualus fabricii		25					
Amphiopholis squamata		26					
Clymenella torquata		27					
Pholoe minuta		28		15	22		
Nereis pelagica		29			24		
Modiolus modiolus		30		26	11		
Caprella linearis		31		33	49		
Balanus balanoides		32			18		
Musculus niger		33		5	10		
Pontogeneia inermis		34		25	4		
Anomia aculeata		35					
Moelleria costulata		36		22	35		
Mitrella dissimilis		37					
Amphitrite cirrata		38					
Cerastoderma pinnulatum		39		16	33		
Balanus sp.		40					
Corpphium sp.		41		29	14		
Hydroides sp.				10	28		
Pectinaria granulata				11	25		
Ischnochiton alba				13	46		
Maldanidae sp.				20	27		
Mya arenaria				21	58		
Crenella descussata				24	45		
Crenella faba				27			
Harmothoe extenuata				30			
Puncturella noachina				31			
Margarites groenlandica				34	36		
Harmothoe imbricata				35			
Nephtys ciliata				36			
Diaphana minuta				37			
Mitrella rosacea				38			
Harmothoe sp.					7		
Janira alta					28		
Syllis armillaris					31		
Henricia sanguinoleuta					32		
Metopa sp.					38		
Dodecaceria concharum					39		
Euclymene collaris					40		
Maldanopsis elogata					41		
Corophium bonelli					42		
Munna fabricii					43		
Eulalia viridis					44		
Thelepus cincinnatus					47		
Phoxocelphalus holbolli					48		
Naineris quadricuspida					50		
Tharyx acutus					51		
Flabelligera affinis					52		
Amphitrite cirrata					53		
Prionospio sp.					55		
Cirratus cirratus					56		
Potamilla reniformis					57		
Metopella carinata					59		
Tonicella marmorea					60		

STATION H12 SPECIES	CRUISE 14	15	16	17	18	19	20
Spirorbis spirillum				1	1	1	1
Spirorbis borealis				2	3	4	2
Ischyrocerus anguipes				3	5		25
Tonicella rubra				4	9	6	10
Hydroides sp.				5			39
Balanus balanoides				6	17	20	17
Sympleustes glaber				7	14		12
Asterias sp.				8	7	11	13
Pholoe minuta				9	31	16	8
Hiatella sp.				10	13	7	30

STATION H12 (Continued) SPECIES	CRUISE 14	15	16	17	18	19	20
Strongylocentrotus droebachiensis				11	18	8	7
Alvania arenaria				12			20
Lacuna vincta				13	19	2	34
Spirorbis violaceus				14		28	22
Metopella angusta				15	6		28
Eualus pusiolus				16	37		45
Nereis pelagica				17	22	23	37
Musculus niger				18	11	12	14
Tonicella marmorea				19	23		44
Buccinum undatum				20		33	57
Modiolus modiolus				21	12	15	15
Caprella linearis				22	26	10	49
Moelleria costulata				23		19	9
Margarites groenlandica				24			46
Pontogeneia inermis					2	3	3
Caprella septentrionalis					4	5	4
Harmothoe sp.					8	13	54
Dodecaceria concharum					10	9	27
Corophium sp.					15		63
Ischnochiton alba					16	18	11
Achelia spinosa					20	31	33
Lepidonotus squamatus					21	14	40
Nicolea venustula					24		
Thelepus cincinnatus					25	27	41
Alvania castanea					27		26
Maldanopsis elongata					28		
Henricia sanguinoleuta					29	21	42
Cucumaria frondosa					30	32	53
Cirratus cirratus					32		51
Mya arenaria					33		36
Nephtys ciliata					34	24	24
Pectinaria granulata					35		5
Cerastoderma pinnulatum					36		38
Tharyx acutus						17	
Nephtys incisa						22	
Myriochele heeri						25	58
Asabellides oculata						26	52
Crenella descussata						29	31
Unicola irrorata						30	23
Onchidoris aspera						34	
Anomia simplex							6
Harmothoe imbricata							16
Tharyx sp.							18
Aricidea jeffreysii							19
Harmothoe extenuata							21
Munna fabricii							29
Melita dentata							32
Anomia aculeata							35
Spio setosa							43
Eulalia viridis							47
Prionospio sp.							48
Exogone dispar							50
Syllis armillaris							55
Notomastus luridus							56
Jassa falcata							59
Acmaea testudinalis							60
Tharyx sp. I							61
Monoculodes sp.							62

STATION H14 SPECIES	CRUISE 14	15	16	17	18	19	20
Spirorbis spirillum		1	1	1		1	1
Ophiopholis aculeata		2		6		9	
Spirorbis borealis		3	4	2		3	5
Ophiura robusta		4				8	
Anomia simplex		5	7	28		14	8
Cerastoderma pinnulatum		6	9			11	28
Tonicella rubra		7	25	12		17	11
Strongylocentrotus droebachiensis		8	8	13		5	6
Eualus fabricii		9					58
Hiatella spp.		10	3	4		10	4
Ischyrocerus anguipes		11	5	3		40	
Margarites groenlandica		12	26	16		37	31
Sympleustes glaber		13	11	5		12	9

Table C-5. (Continued)

STATION H14 (Continued) SPECIES	CRUISE 14	15	16	17	18	19	20
Lacuna vincta		14	13	17		31	44
Musculus discors		15		21		45	
Ischnochiton alba		16	20			25	27
Moelleria costulata		17	16	22		27	21
Caprella septentrionalis		18	24	15		4	2
Caprella linearis		19	15	8		26	52
Asterias sp.		20	34	20		18	38
Alvania castanea		21	17	18		23	60
Achelia spinosa		22	19			22	46
Amphipholis squamata		23				34	
Alvania areolata		24	22	23		42	34
Lepidonotus squamatus		25		30			
Nereis pelagica		26	31	32		43	47
Spirorbis violaceus		27		26		39	42
Cucumaria frondosa		28					43
Balanus balanoides		29	10	19		2	3
Velutina laevigata		30					61
Maldanidae sp.		31					
Modiolus modiolus		32	21	27		13	25
Crenella decussata		33	28			29	30
Pontogeneia inermis		34	32	9		6	20
Anomia aculeata		35	6			24	12
Pectinaria granulata		36	14			36	29
Crenella faba		37					50
Colus stimpsoni		38					
Alvania arenaria		39	29				53
Mitrella rosacea		40					62
Hydroides sp.		41	2	7		7	32
Eualus pusiolus			12	10		41	15
Metopella angusta			18	14		21	19
Musculus niger			23	11		15	13
Colus sp.			27	34		49	
Pholoe minuta			30	25		35	24
Mya arenaria			33			48	56
Monoculodes sp.				24		30	17
Harmothoe imbricata				29			18
Eulalia viridis				31			
Henricia sanguinoleuta				33			
Harmothoe sp.						16	33
Unicola irrorata						19	7
Corophium sp.						20	14
Maldanopsis elongata						28	41
Thulepus cincinnatus						32	45
Euclymene collaris						33	22
Syllis armillaris						19	20
Dodecaceria concharum						38	54
Myriochele heeri						44	35
Tharyx acutus						46	
Harmothoe extenuata						47	
Exogone dispar							16
Photis reinhardi							23
Enoplobranchus sanguineus							26
Phyllodoce mucosa							36
Munna fabricii							37
Notomastus luridus							39
Naineris quadricuspida							40
Prionospio sp.							48
Melita dentata							49
Spio setosa							51
Eudorella emarginata							55
Margarites helcina							57
Aricidea jeffreysii							59
Cirratulus cirratus							63
Aequipecten irradians							64
Astarte undata							65
Nassarius trivittata							66
Nephtys incisa							67
Tharyx sp.							68

STATION C6 SPECIES	CRUISE 14	15	16	17	18	19	20
Euclymene collaris		1			1	1	1
Phyllodoce sp.		2					
Praxillellia gracilis		3					
Ophiopholis aculeata		4					
Strongylocentrotus droebachiensis		5			14	5	5

STATION C6 (Continued) SPECIES	CRUISE 14	15	16	17	18	19	20
Unicola irrorata		6			3	2	2
Ischnochiton alba		7			16	9	6
Corophium crassicorne		8			5		
Scoloplos fragilis		9					
Syllidae sp.		10					
Glycera capitata		11			4	6	10
Cerastoderma pinnulatum		12			11	16	14
Exogone dispar					2	3	3
Euchone rubrocincta					6	15	23
Spio setosa					7	11	11
Phyllodoce mucosa					8	13	8
Tharyx acutus					9	12	
Corophium sp.					10	4	4
Syllis armillaris					12	8	
Syrrhoe crenulata					13		
Spirorbis spirillum					15	24	
Myrochele heeri					17		22
Erichthonius robricornis					18		
Nephtys ciliata					19	23	
Moelleria costulata					20	25	
Microprotopus sp.					21		
Harmothoe sp.					22	10	
Monoculodes sp.					23	7	7
Lunatia triseriata					24		
Aricidea jeffreysii					25	26	
Notomastus luridus					26		
Crenella decussata					27		
Pholoe minuta						14	13
Owenia fusiformis						17	
Naineris quadricuspida						18	17
Paraonis gracilis						19	
Diastylis quadrispinosa						20	
Modiolus modiolus						21	25
Tharyx sp. 1						22	9
Crenella faba						27	26
Astarte borealis						28	
Edotea montosa						29	
Musculus niger						30	24
Melita dentata						31	
Margarites groenlandica						32	
Harmothoe extenuata							12
Harmothoe imbricata							15
Enoplobranchus sanguineus							16
Caprella septentrionalis							18
Margarites helicina							19
Anonyx lilljeborgi							20
Lunatia immaculata							21
Phoxichilidium femoratum							27
Asterias sp.							28
Buccinum undatum							29
Nephtys incisa							30
Onchidoris sp.							31

STATION D2 SPECIES	CRUISE 14	15	16	17	18	19	20
Euclymene collaris			1				
Phyllodoce mucosa			2				
Syllis armillaris			3				
Glycera capitata			4				
Tharyx acutus			5				
Owenia fusiformis			6				
Exogone dispar			7				
Pholoe minuta			8				
Euchone rubrocincta			9				
Spio setosa			10				
Nephtys ciliata			11				
Aricidea jeffreysii			12				
Myriochele heeri			13				
Asabellides oculata			14				
Naineris quadricuspida			15				
Ophiopholis aculeata			16				
Thelepus cincinnatus			17				
Chone infundibuliformis			18				
Crenella faba			19				
Astarte borealis			20				
Cerastoderma pinnulatum			21				
Mya arenaria			22				
Harmothoe sp.			23				

Table C-5. (Continued)

STATION D3

SPECIES	14	15	16	17	18	19	20
Euclymene collaris				1			
Unciola irrorata				2			
Exogone dispar				3			
Corophium crassicorne				4			
Spirorbis spirillum				5			
Spirorbis borealis				6			
Phyllodoce mucosa				7			
Strongylocentrotus droebachiensis				8			
Moelleria costulata				9			
Glycera capitata				10			
Ischnochiton alba				11			
Caprella septentrionalis				12			
Spio setosa				13			
Astarte borealis				14			
Cerastoderma pinnulatum				15			
Tharyx sp.				16			
Crenella faba				17			
Cardita borealis				18			
Corophium sp.				19			
Nephtys ciliata				20			
Naineris quadricuspida				21			
Pholoe minuta				22			
Echone rubrocincta				23			
Harmothoe sp.				24			
Notomastus luridus				25			
Leptocheirus pinguis				26			
Margarites groenlandica				27			
Aricidea jeffreysii				28			
Modiolus modiolus				29			
Diaphana minuta				30			
Melita dentata				31			
Aeginina longicornis				32			
Buccinum undatum				33			
Harmothoe imbricata				34			
Crenella decussata				35			
Enoplobranchus sanguineus				36			
Thelepus cincinnatus				37			
Mya arenaria				38			
Asterias sp.				39			
Tharyx acutus				40			
Erichthonius rubricornis				41			
Monoculodes tuberculatus				42			
Syrrhoe crenulata				43			
Margarites helicina				44			
Harmothoe extenuata				45			
Eteone flave				46			
Myriochele heeri				47			
Owenia fusiformis				48			
Ischyrocerus anguipes				49			
Caprella linearis				50			
Eualus pusiolus				51			
Monoculodes sp.				52			

STATION C11

SPECIES	14	15	16	17	18	19	20
Unicola irrorata				1	1	1	1
Tharyx sp.				2	2	6	3
Euclymene collaris				3	7	2	2
Orchomenella sp.				4			
Travisia carnea				5	16		
Exogone dispar				6	12	4	5
Owenia fusiformis				7	13	8	6
Aricidea jeffreysii				8	11	16	10
Euchone rubrocincta				9	9	7	7
Nephtys ciliata				10	5	12	34
Crenella decussata				11		37	
Notomastus luridus				12	10	19	4
Corophium sp.				13		15	21
Myriochele heeri				14	15	24	13
Phyllodoce mucosa				15	21	5	8
Crenella glandula				16			
Ischnochiton alba				17	8	20	27
Enoplobranchus sanguineus				18	35		29
Glycera capitata				19	25	22	25
Modiolus modiolus				20	17	23	22
Crenela faba				21	4	41	

STATION C11 (Continued)

SPECIES	14	15	16	17	18	19	20
Leptocheirus pinguis				22	6	10	15
Pectinaria granulata				23	22	33	19
Corophium crassicorne				24	3		
Jassa falcata				25		39	14
Scoloplos fragilis				26	18	9	
Spio setosa				27	20		9
Nassarius trivittata				28	23	25	12
Lumbrineris tenuis				29			
Diastylis sculpta				30		30	33
Pholoe minuta				31	26	11	18
Chone infundibuliformis				32			26
Cerastoderma pinnulatum				33	27	38	
Lora pleurotumania				34	33		
Diastylis polita				35	19		
Asterias sp.				36			
Spio sp.				37			
Lunatia immaculata				38			
Goniada maculata				39	29		
Polydora ligna				40		13	11
Asabellides oculata				41			31
Mararites helicina				42			
Moelleria costulata				43			
Nephtys incisa				44		44	16
Polycirrus eximius				45			
Orchomenella minuta				46			
Caprella linearis				47			
Edwardsia elegans				48			30
Eteone flava				49		31	
Monocluodes tuberculatus				50	31		
Phyllodoce maculata					14		
Caprella septentrionalis					24		37
Strongylocentrotus droebachiensis					28	28	20
Anonyx sarsi					30		
Margarites groenlandica					32		
Nephtys sp.					34		
Phyllodocida sp.					36		
Tharyx acutus						3	
Syllis armillaris						14	
Tharyx sp. I						17	
Harmothoe sp.						18	
Harmothoe imbricata						21	17
Scolelepides viridis						26	
Anonyx lilljeborgi						27	39
Etone sp.						29	
Spirorbis spirillum						32	
Melita dentata						34	
Metopella angusta						35	
Monoculodes sp.						36	
Prionospio sp.						40	35
Ischyrocerus anguipes						42	
Edotea montosa						43	28
Harmothoe extenuata							23
Phyllodoce groenlandica							24
Pontogeneia inermis							36
Phoxichilidium femoratum							32
Odontosyllis fulgurans							38

STATION M6

SPECIES	14	15	16	17	18	19	20
Travisia carnea	1		4		4		
Sternapsis scutata	2		3	3		8	7
Ninoe nigripes	3		1	2	2	2	5
Maldane sarsi	4		2	4	1	6	3
Nucula delphinodonta	5		5	7	3	4	6
Scoloplos fragilis	6		6	5		5	8
Edotea montosa	7			12	6	9	9
Pholoe minuta	8			9	12	10	10
Periploma papyratium	9		14	10	7	12	12
Lumbrineris fragilis	10		8		10	17	16
Harmothoe imbricata	11			16			18
Goniada maculata	12		7				15
Praxillella gracilis	13		12	13	9	14	17
Ptilanthura tenuis	14						
Nassarius trivittata	15			15			25
Cerastoderma pinnulatum	16			18		21	27
Phyllodoce maculata	17						

Table C-5. (Continued)

STATION M6 (Continued)

SPECIES	14	15	16	17	18	19	20
Crenella glandula	18						
Axinopsis orgiculatus	19		13				
Nephtys ciliata	20						
Hippomedon propinquus			9				
Spio sp.			10				
Tracia sp.			11				
Edotea triloba			15				
Polynoidae sp.			16				
Tharyx sp.				1		1	2
Spio setosa				6		7	1
Paranois gracilis				8		13	11
Gonidada maculata				11		11	
Thracia myopsis				14		19	21
Mya arenaria				17			
Crenella decussata				19	11	18	22
Astarte undata				20	8		
Anachis haliaecti					5		
Cyathura polita							
Ophelia sp.						3	4
Euclymane collaris						15	
Axinopsis orbiculatus						16	26
Tharyx acutus						20	28
Cyathura burbancki						22	19
Prionospio sp.							13
Notomastus luridus							14
Harmothoe sp.							20
Naineris quadricuspida							23
Anonyx lilleborgi							24
Eudorella emarginata							29
Apistobranchus tullbergi							30

STATION M7

SPECIES	14	15	16	17	18	19	20
Ninoe nigripes			1	1	1	1	1
Nephtys ciliata			2	15	3	5	
Scoloplos fragilis			3	2		3	4
Modiolus modiolus			4	8		9	9
Edotea montosa			5	4	2	2	3
Cerastoderma pinnulatum			6	16	6	14	
Edotea triloba			7				
Eudorella truncatula			8				
Lumbrineris fragilis			9				
Owenia fusiformis			10	3		8	
Photis reinhardi			11	6	5	6	
Nucula delphinodonta			12	11		12	
Travisia carnea			13				
Nephtys sp.				5			7
Nephtys incisa				7			
Pholoe minuta				9		11	5
Eudorella emarginata				10		15	11
Tharyx sp.				12			8
Ampelisca sp.				13		17	
Eteone sp.				14			
Nassarius trivittata				17	4	10	6
Diastylis sculpta						4	2
Prionospio sp.						7	
Aricidea jeffreysii						13	
Hippomedon serratus						16	
Axinopsis orbiculatus						18	
Thracia myopsis						19	
Corophium sp.						20	
Diastylis quadrispinosa						21	
Ophelia sp.						22	
Crenella decussata						23	10
Orchomenella sp.						24	
Ampelisca sp.							12

STATION M8

SPECIES	14	15	16	17	18	19	20
Tharyx sp.			1	1			2
Spio setosa			2	2			
Ninoe nigripes			3	4	1	2	6
Pholoe minuta			4	3		3	5
Thracia myopsis			5	6		9	12
Scoloplos fragilis			6	5	4	4	7
Prinospio sp.			7				
Edotea montosa			8	7	5	1	4
Paraonis gracilis			9	11			
Modiolus modiolus			10				
Photis reinhardi			11				
Cerastoderma pinnulatum			12	10	7	11	17
Eudorella emarginata			13	13		13	15
Pseudunciola obliqua			14				
Astarte undata			15	8		6	13
Nucula delphinodonta			16	12		8	16
Eteone sp.			17				14
Goniada maculata			18	14			
Nassarius trivittata			19				
Lumbrineris fragilis			20				
Phyllodoce mucosa			21				
Myriochele heeri			22	9			9
Chaetoderma nitidulum				15			
Nephtys sp.				16			
Nephtys incisa				17			20
Ampelisca sp.				18			
Travisia carnea					2		
Axinopsis sp.					3		
Astarte elliptica					6		
Praxillura ornata					8		
Nucula sp.					9		
Ophelia sp.						7	
Crenella decussata						10	
Axinopsis orbiculatum						12	19
Anonyx lilljeborgi						14	
Prionospio sp.							3
Harmothoe imbricata							8
Polydora ligna							10
Astarte borealis							11
Pectinaria granulata							18

STATION M9

SPECIES	14	15	16	17	18	19	20
Owenia fusiformis			1	1		1	1
Photis reinhardi			2	2		7	12
Modiolus modiolus			3	4		2	3
Pseudunciola obliqua			4	3		3	4
Tharyx sp.			5				2
Edotea montosa			6	9		9	13
Pholoe minuta			7	7		6	7
Aricidea jeffreysii			8			10	9
Prionospio sp.			9	20		4	5
Corophium sp.			10	12		12	10
Phyllodoce mucosa			11	10		11	14
Cerastoderma pinnulatum			12	19		25	24
Diastylis sculpta			13	11		17	6
Scoloplos fragilis			14	5		8	8
Myriochele heeri			15				31
Diastylis polita.			16			26	30
Arctica islandica			17	18		15	15
Nephtys incisa			18				17
Chiridotea tuftsi			19	13		24	11
Nephtys sp.			20				
Tellina agilis			21	14		19	26
Ninoe nigripes			22	17		23	25
Nephtys sp.			23	6		13	34
Corophium crassicorne				8			
Spiophanes bombyx				15		18	23
Orchomenella sp.				16		20	20
Phoxocephalus holbolli				21			
Tharyx acutus						5	39
Spio setosa						14	18
Polydora ligna						16	16
Nucula delphinodonta						21	22
Ophelia sp.						22	
Nassarius trivittata						27	
Axinopsis orbiculatus						28	40
Asthenothaerus sp.						29	37
Eteone flava						30	
Dulichia porrecta						31	
Lunatia triseriata						32	
Notomastus luridus							19
Nephtys picta							21

Table C-5. (Continued)

STATION M9 (Continued)	CRUISE						
SPECIES	14	15	16	17	18	19	20
Tharyx sp. II							27
Echinarachnius parma							28
Tharyx sp. I							29
Eteone sp.							32
Eudorella emarginata							33
Pectinaria granulata							35
Halcampa duodecimirrata							36
Edwardsia elegans							38

STATION S10	CRUISE						
SPECIES	14	15	16	17	18	19	20
Euclymene collaris			1	1		1	1
Pseudunciola obliqua			2	2	1	2	2
Uniciola irrorata			3			16	12
Modiolus modiolus			4	4	6	3	4
Corophium sp.			5	8		14	10
Nephtys incisa			6	3		8	3
Tharyx sp.			7				
Nephtys ciliata			8	6	4	7	19
Spiophanes bombyx			9			4	6
Phyllodoce mucosa			10				14
Photis reinhardi			11				
Nephtys sp.			12	9			
Corophium crassicorne			13				
Scoloplos fragilis			14			15	16
Pholoe minuta			15				
Prionospio sp.			16				
Lunatia triseriata			17				
Owenia fusiformis			18				
Edwardsia elegans				5		9	7
Diastylis sculpta				7		10	5
Cerastoderma pinnulatum				10		5	
Ninoe nigripes				11			
Edotea montosa				12		12	9
Jassa falcata					2		
Maldanidae sp.					3		
Pontogeneia inermis					5		
Ischyrocerus anguipes					7		
Nassarius trivittata					8	13	13
Diastylis polita					9		
Nephtys picta						6	
Polydora ligna						11	11
Nippomedon serratus						17	20
Exogone dispar							8
Spio setosa							15
Tharyx acutus							17
Monoculodes sp.							18

* U.S. Government Printing Office: 1977-777-045/1259 Region 8

DATE DUE			
GAYLORD	No. 2333		PRINTED IN U.S.A.